Syntheses of Functionalised [2.2]Paracyclophanes-Structure and Reactivity Studies

Von der Gemeinsamen Naturwissenschaftlichen Fakultät
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von
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Mere words are insufficient to express my thanks to my **mother** and **uncle** for their love, affection and support.

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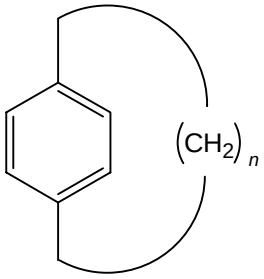
To my mother

Contents

1. Introduction

The emergence of cyclophane chemistry as a separate field of aromatic chemistry began with the classic studies carried out by Donald J. Cram in the early 1950s. In 1951, Cram and Steinberg[1] coined the term "paracyclophane" **1** indicating that these *cyclic* aromatic compounds consist of a *phenyl* and a bridging *alkane* unit.[2] The nomenclature for this class of compounds was developed over a number of years, starting from 1930 by Wieland *et al.*,[3] in the 1930s and 1940s by Lüttringhaus, who recognised certain stereochemical relationships of dissymmetry in these cyclic systems and choose to name them as "Ansa-compounds"[4] [Ansa (Latin) meaning – handle] since the bridges looked like handles to the ring when portrayed in two dimensions. Early contributions came from Schubert *et al.*[5] in 1954 and Cram and Abell[6] in 1955 who considered most systems of benzene rings with all carbon or hetero-carbon bridges. Vögtle and Neumann in 1970 contributed further to the cyclophane nomenclature. The first part of the phane nomenclature developed by the International Union of Pure and Applied Chemistry (IUPAC) was published in 1998.[7] Cyclophanes have lead to a new field of research called host-guest chemistry or supramolecular chemistry. Donald J. Cram together with Charles J. Pedersen and Jean-Marie Lehn received the Nobel Prize for his pioneering work in the field of host-guest chemistry in 1987.

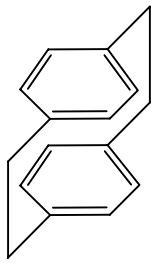


1

Scheme 1. General structure of a paracyclophane.

There has always been interest in relationships between structure and physical and chemical properties of aromatic hydrocarbons, which may additionally be strained or sterically hindered. [2.2]Paracyclophane (**2**) is one such phane which has interested chemists, theoreticians and industrialists over many years and has been studied extensively. [2.2]Paracyclophane is a multi ton industrial product used as a monomer in polymer chemistry (see below). Though the benzene rings of this sandwich structured molecule are

bent (non planar) due to the short ethano bridges, they still exhibit aromatic character as shown by spectral data and chemical reactivity studies. The strain caused by this molecular deformation produces strain energy of ca. 30 kcal/mol.



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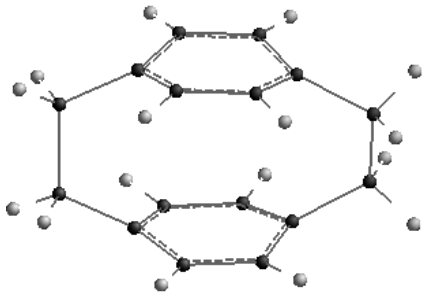
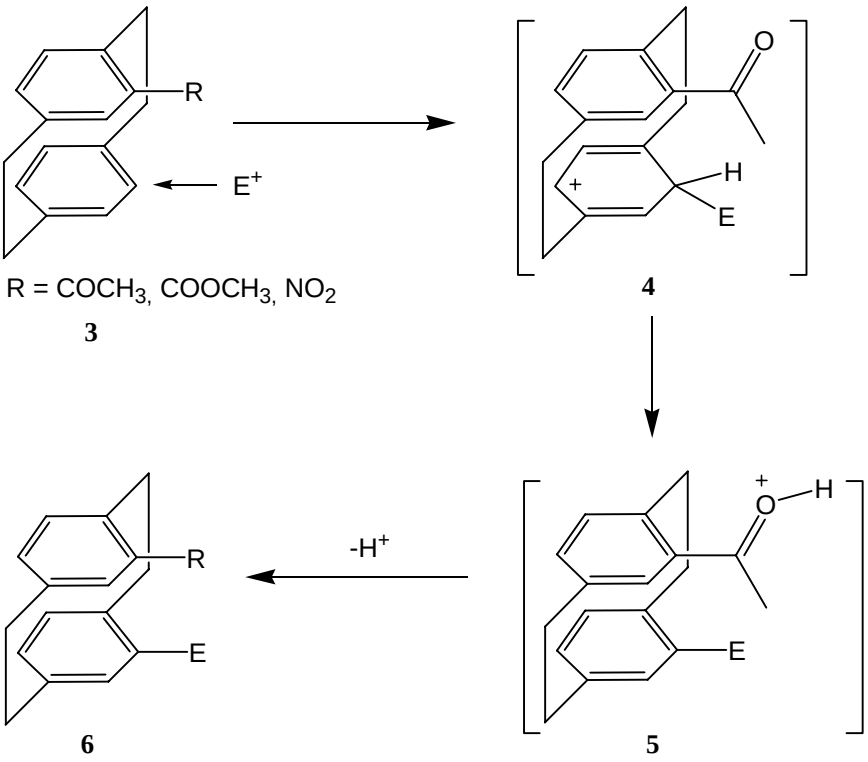


Scheme 2. Structure of [2.2]paracyclophane (**2**).

The chemistry of **2** can be divided into two major types namely (a) aromatic nucleus chemistry and (b) bridge chemistry. This dissertation deals mainly with aromatic nucleus (phenyl ring) chemistry. The fact that cyclophane chemistry is a rapidly evolving field is demonstrated by a recent monograph (Gleiter and Hopf)[61] that - *inter alia* - describes the application of cyclophane in stereoselective synthesis, material science, basic organic and supramolecular chemistry. More and more the importance of cyclophanes as partial structures of molecular machines is recognised.

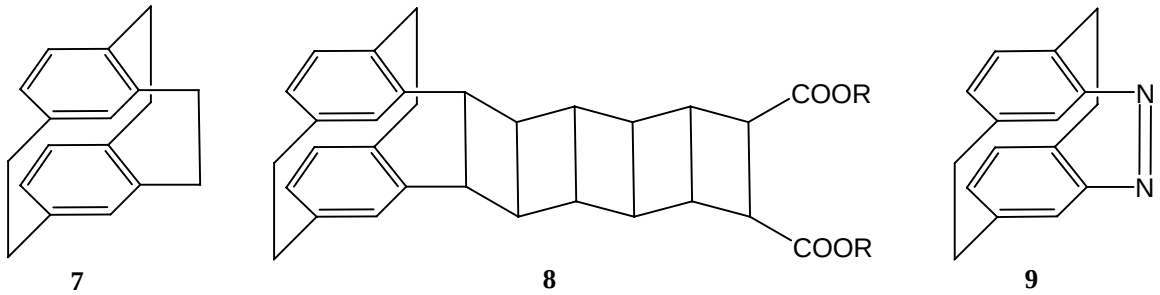
1.1 Intramolecular directing effect

In principle the substituents play a leading role in determining the steric and electronic effects of a molecule, which in term affects the physical (melting point, structural conformation etc.) and chemical (derivatisation etc.) properties. In monofunctionalised [2.2]paracyclophanes (**3**) bearing a carbonyl or a nitro functionality, when subjected to electrophilic aromatic reactions, the substituent tends to direct the incoming electrophile to the so called *pseudo-geminal* position. It was first proposed by Cram in one of his earliest work,[8] that this high regioselective reaction proceeds through the formation of the σ-complex (**4**). The aromatic hydrogen is displaced to the neighbouring carbonyl group which is oriented in optimal position for this slow intramolecular proton transfer to take place. Thus generated intermediate **5** undergoes deprotonation to give the *pseudo-geminally* substituted cyclophane **6**.



Scheme 3. Electrophile directed to the *pseudo-geminal* position.

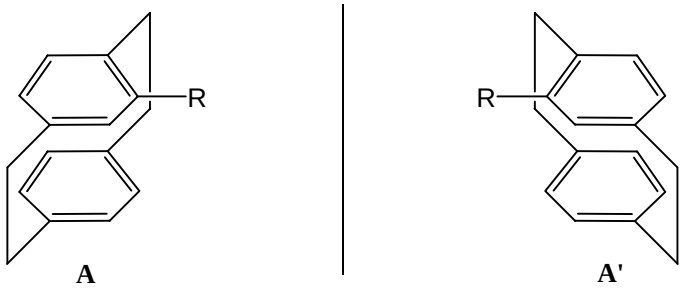
This intramolecular directing effect has lead to the preparation of multibridged cyclophanes **7**[9], ladderanes **8**[10], the first multibridged cyclophane with a bridge consisting of only heteroatoms **9**[11] and many strained compounds.



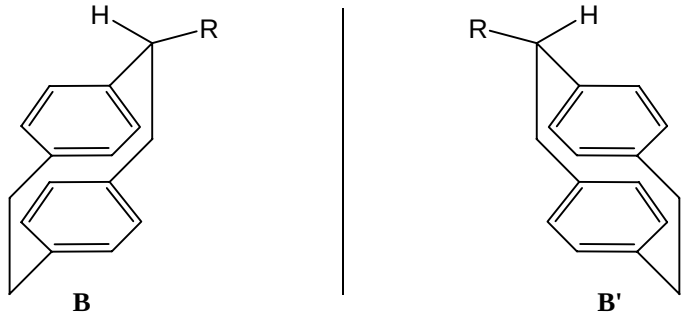
Scheme 4. Recent examples of *pseudo-geminally* bridged [2.2]paracyclophane.

1.2 Chirality in [2.2]paracyclophanes

Any monosubstituted [2.2]paracyclophane is chiral. When the substituent R is positioned in the aromatic ring (**A**), the derivative posses a plane of chirality. When the substituent is bound to a bridge carbon atom (**B**), the derivative has a centre of chirality.

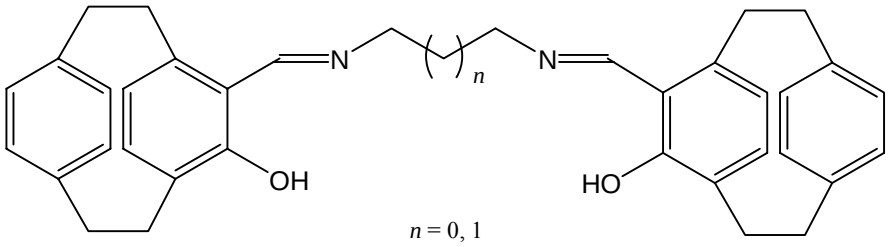


A **A'**



B **B'**

Obviously, when the substituents are also chiral in nature this gives rise to diastereomers. Chiral [2.2]paracyclophanes are increasingly used in asymmetric synthesis.



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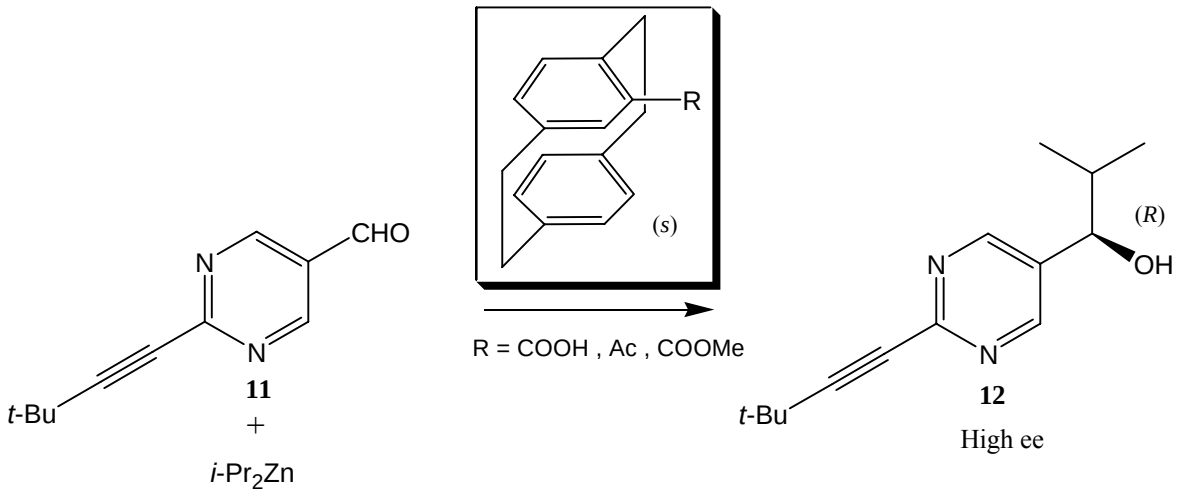
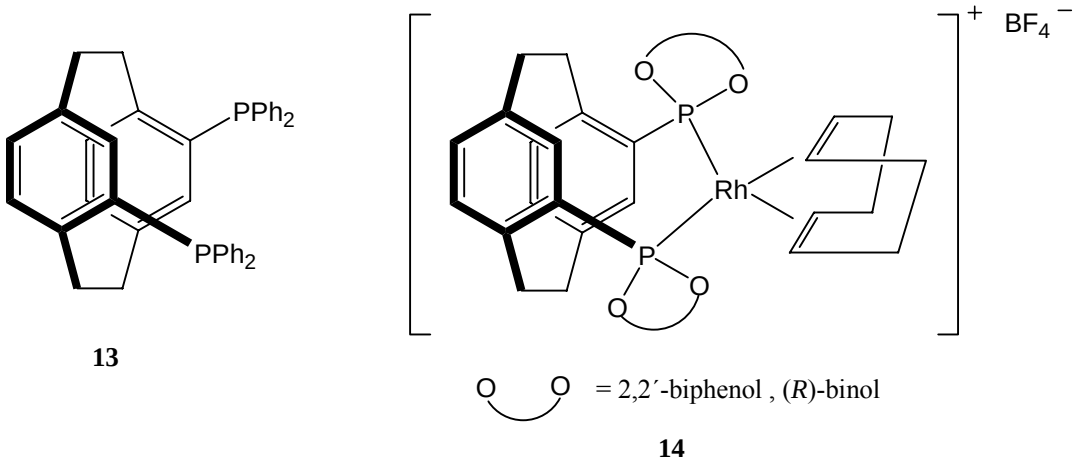
Scheme 5. A chiral catalyst based on FHPC (Formylhydroxy[2.2]paracyclophane).

For example compound **10**,[12] (n = 0) in which the only elements of chirality are the two disubstituted [2.2]paracyclophane moieties has been effective (84% ee) for the enantioselective trimethylsilylcyanation of benzaldehyde. Interestingly the catalyst could be recovered by simple precipitation and could be reused for at least five more times without loss of activity. On the other hand when the link between both ethylenediamine moieties was a propylene spacer (n = 1) major losses of enantioselectivity and especially of activity were observed.



Scheme 6. Asymmetric synthesis of a 2-alkynylpyrimidyl alkanol.

[2.2]Paracyclophanes bearing carboxyl, acetyl or carboxymethyl groups as functionality were found to act as chiral initiators in an enantioselective addition of diisopropylzinc to 2-alkynylpyrimidine-5-carbaldehyde (**11**) to afford 2-alkynylpyrimidyl alkanol (**12**) (Scheme 6) with up to 97% ee.[13] Many chiral catalysts have been prepared using the chiral ligand PhanePhos **13**. One such compound is the rhodium based catalyst **14** bearing biphenoxy and binaphthoxy groups at its P atoms, has been used in the asymmetric hydrogenation of dehydroamino acids and esters with a selectivity of up to 98.5% ee.[14]

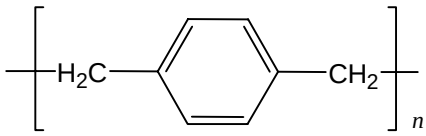


Scheme 7. The chiral ligand PhanePhos **13** and Rh-catalyst **14** prepared from it.

1.3 Polymerisation by Chemical Vapour Deposition (CVD)

As already mentioned [2.2]paracyclophane, a multi ton industrial compound, is mainly used for the preparation of polymers known under the trade name “Parylene”, **15**. Parylene, unlike

other polymeric materials, is not manufactured or sold as a polymer, but rather produced by vapour phase deposition (CVD) and polymerisation of *para*-xylylene, generated by the thermolysis of [2.2]paracyclophane (**2**). This method of deposition produces a unique quality of coating in a completely uniform manner. Parylene is extremely resistant to chemical attack, exceptionally low in trace metal contamination, has superior dielectric strength, excellent mechanical strength, high surface and volume resistivities and other desirable electrical properties.



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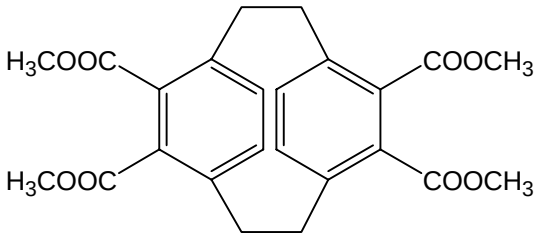
Scheme 8. Structure of Parylene.

In principle, functionalised [2.2]paracyclophanes are more useful in this approach for coatings as the functionality extends the possibility of further derivatisation of the substituent and changes that can be carried out after polymerisation according to needs. In biomaterial research for example, there is a strong interest in new materials that have improved biocompatibility. These biomaterials have medical applications as they can be implanted in the human body. Polymers of poly(*p*-xylylene) show an extraordinarily high biostability compared to common polymer coatings. Monofunctionalised [2.2]paracyclophanes[15] bearing functionalities like trifluoroacetyl, amino, hydroxymethyl and also multifunctionalised [2.2]paracyclophanes like 4,5,12,13-tetrakis(methoxycarbonyl)[2.2]paracyclophane (**16**)[36] have been used in CVD and found to have good compatibility. 4-Chloro[2.2]paracyclophane (**17**) forms good polymers by CVD and also exhibits good haemocompatibility of metallic stents.[16]



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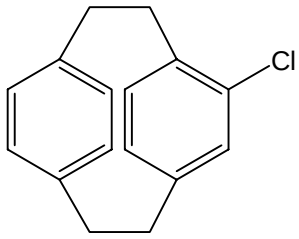

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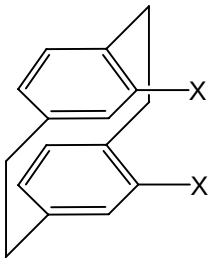
Scheme 9. Examples of functionalised [2.2]paracyclophanes used in CVD.

1.4 Aim of the work

Though [2.2]paracyclophane chemistry has been explored extensively over the past 50 years, there are still many unsolved problems, both in the areas of classical chemistry and modern application oriented chemistry. The following selection of topics, that are addressed in this thesis, is typical for modern [2.2]paracyclophane chemistry.

1.4.1 *Pseudo-geminal* dihalogen derivatives

The halogen derivatives, namely the dihalogen derivatives of [2.2]paracyclophane have been used extensively in further synthesis and derivatisation. Most of the metal-organic chemistry is based on halogenated compounds. Looking back into the history of dihalogenated [2.2]paracyclophane compounds, although most of the possible isomers were synthesised, the *pseudo-geminally* disubstituted were lacking. Only recently difluoro[2.2]paracyclophane (**18**)[17] was reported, but only as a mixture of four isomers. The synthesis of exotic molecules like the ladderanes **8** which demonstrate topochemical principles and multibridged cyclophanes, all require *pseudo-geminally* substituted precursors.



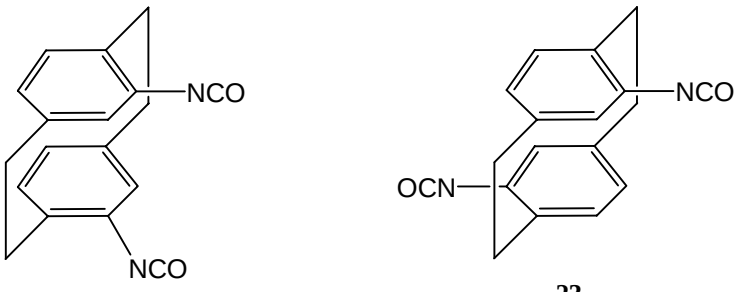
X	F	Cl	Br	I
	18	**19**	**20**	**21**

Scheme 10. The *pseudo-geminally* substituted dihalo[2.2]paracyclophane derivatives.

The synthesis of the halogen derivatives is also interesting from the structural point of view: as the size of the halogen atom increases, the strain of the molecule grows thus affecting the aromatic moiety and also the C–C bridge bond. It is also interesting to study the through space interaction of the fluorine substituents (F–F interaction and F–H interaction) by NMR investigations.[11, 17]

1.4.2 Diisocyanato[2.2]paracyclophane

Chiral phanes are increasingly applied in asymmetric synthesis.[61] *Pseudo-ortho* substituted [2.2]paracyclophanes posses a C_2-axis and are hence chiral. These functionalised cyclophanes could also prove to be good starting materials for CVD polymerisations, as then each aromatic ring of the polymer would bear the functional group. 4-Isocyanato[2.2]paracyclophane when subjected to CVD polymerisation was found to form good polymers with the isocyanate group intact (see Section 2.7). Hence the *pseudo-ortho*-diisocyanato[2.2]paracyclophane (**22**) could prove to be a very good starting material for further derivatisations to provide amines, ureas, amides and other nitrogen containing compounds, in the preparation of chiral catalysts and for CVD polymerisation. The isomeric *pseudo-para*-diisocyanato[2.2]paracyclophane (**23**) is also interesting from the point of view of polymerisation by CVD and also in terms of its stability, packing and structural conformation due to its symmetry.



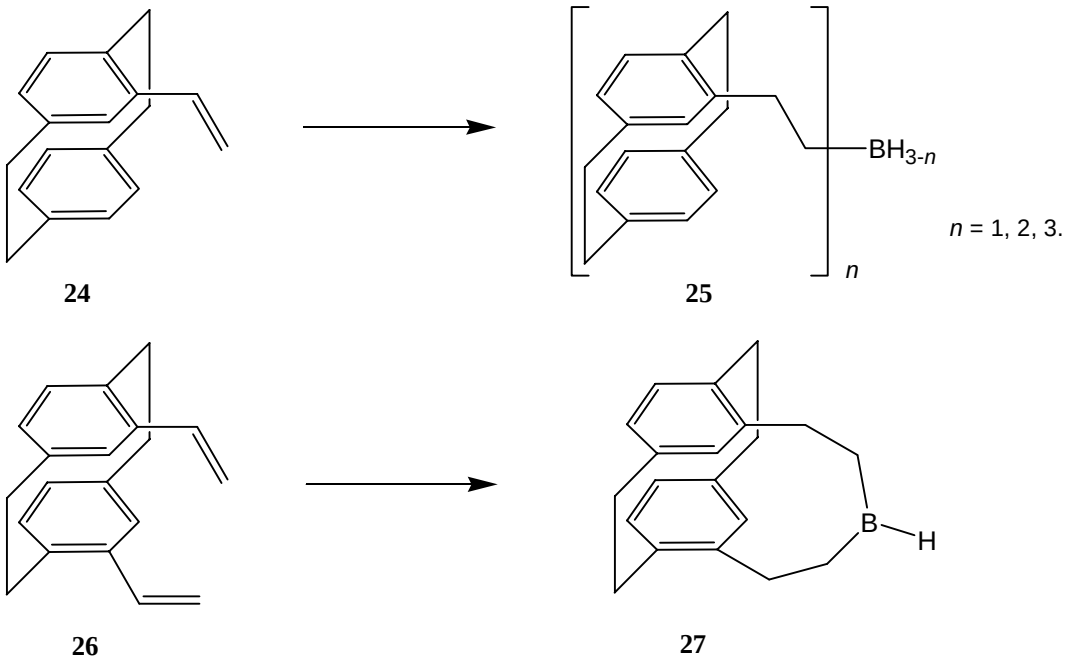
22 **23**

Scheme 11. *Pseudo-ortho*- (**22**) and *pseudo-para*-diisocyanato[2.2]paracyclophane (**23**) respectively.

1.4.3 Chiral hydroborating reagents

Borane and alkylborane reagents are powerful and selective reducing agents. The Lewis acidity of borane (BH_3) causes interesting differences in reducing power compared with other reducing reagents. It was Brown who discovered in the 1970s that alkenes reacted with boranes in ether solvents to form trialkyl boranes. Since then countless hydroborating reagents have been synthesised and many are commercially available. If an optically active compound is used in the hydroboration sequence, the product could also be optically active, provided the C=C moiety of the alkene contains prochiral carbon atoms. Several chiral alkylboranes have indeed been developed by the reaction of borane with naturally occurring chiral alkenes. The most prominent of such chiral hydroborating agents are diisopinocampheylborane,

monoisopinocampheylborane and dilongifolylborane. When these chiral boranes add to prochiral alkenes, addition of the borane proceeds with high asymmetric induction and high diastereoselectivity. 4-Ethenyl[2.2]paracyclophane (**24**) and 4,16-diethenyl[2.2]paracyclophane (**26**) are chiral molecules which could be easily prepared from the corresponding aldehydes by Wittig reaction in good yields. So the aim was to prepare chiral borating agents **25** and **27** by reaction of ethenyl paracyclophane with borane which could be applied for further chiral reduction reactions.



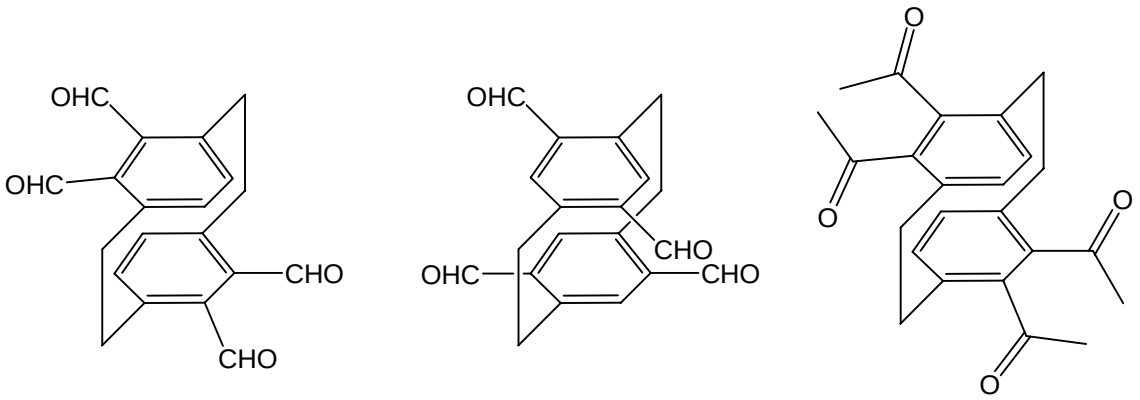
24 **25**

26 **27**

Scheme 12. Chiral [2.2]paracyclophane hydroborating agents.

1.4.4 Tetrafunctionalised [2.2]paracyclophanes

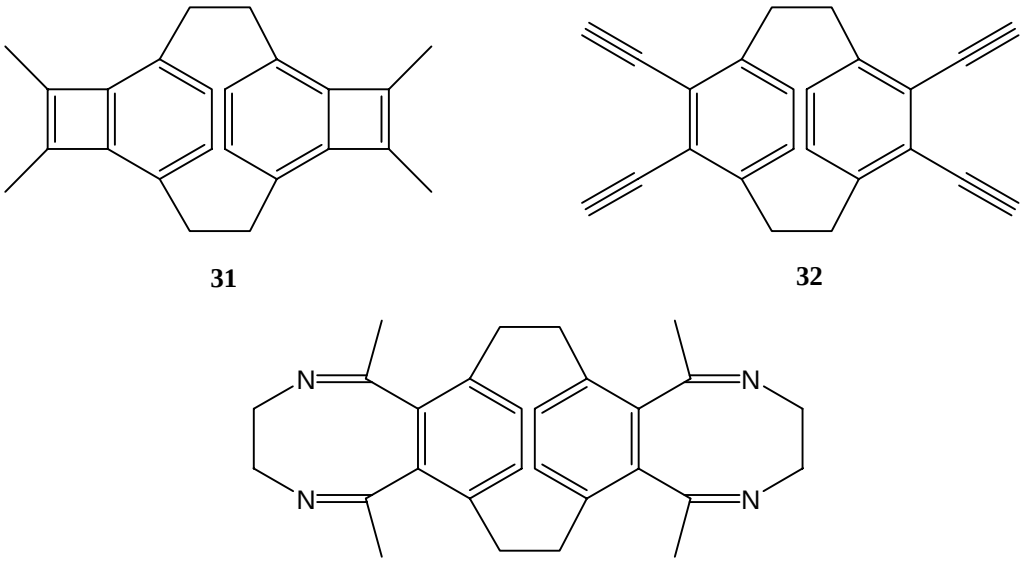
In [2.2]paracyclophane the normal pattern of tetra substitution is either 4,5,12,13 ("*anti*") or 4,7,12,15 ("*crossed*"). Recently the synthesis of 4,5,12,13-tetraformyl[2.2]paracyclophane (**28**)[18] was accomplished but unfortunately the results were irreproducible. The *crossed*-tetraformyl isomer (**29**)[19] was also reported but none of the spectroscopic data are available.



28 **29** **30**

Scheme 13. A selection of tetrafunctionalised [2.2]paracyclophanes.

The syntheses of these tetraformyl derivatives are important as they are suitable starting materials for the annulation of carbo and heterocyclic rings, as the aldehyde functional groups are amenable to Wittig and other carbonyl condensation and coupling reactions. An alternative compound which could serve as a substitute to the tetraformyl derivative is 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**), which could be a good starting material for the synthesis of compound **31**, for the synthesis of the tetraethynyl compound **32** and also many other heterocyclic compounds like **33**. These multifunctionalised phanes are also interesting molecules for CVD polymerisation. The preparation of several lower ethynylogs of **32** has recently been described.[62]

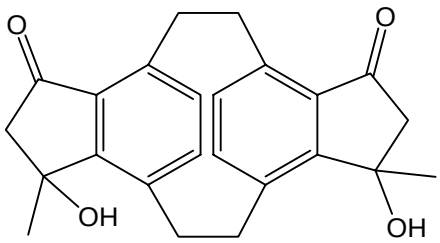


31 **32**

33

Scheme 14. Some derivatives from 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**).

Furthermore aldol condensation of **30** would lead to the formation of chiral alcohols (**34**, **35**). In principle there are six isomers possible and this makes the stereochemical studies of this reaction more interesting. Moreover dehydration of these alcohols would lead to the formation of a new class of phane molecules "indenonophanes", with compound **36** serving as an example.



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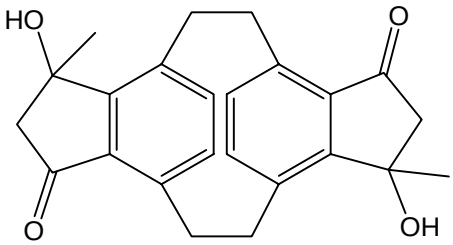

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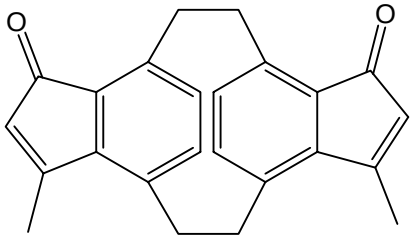

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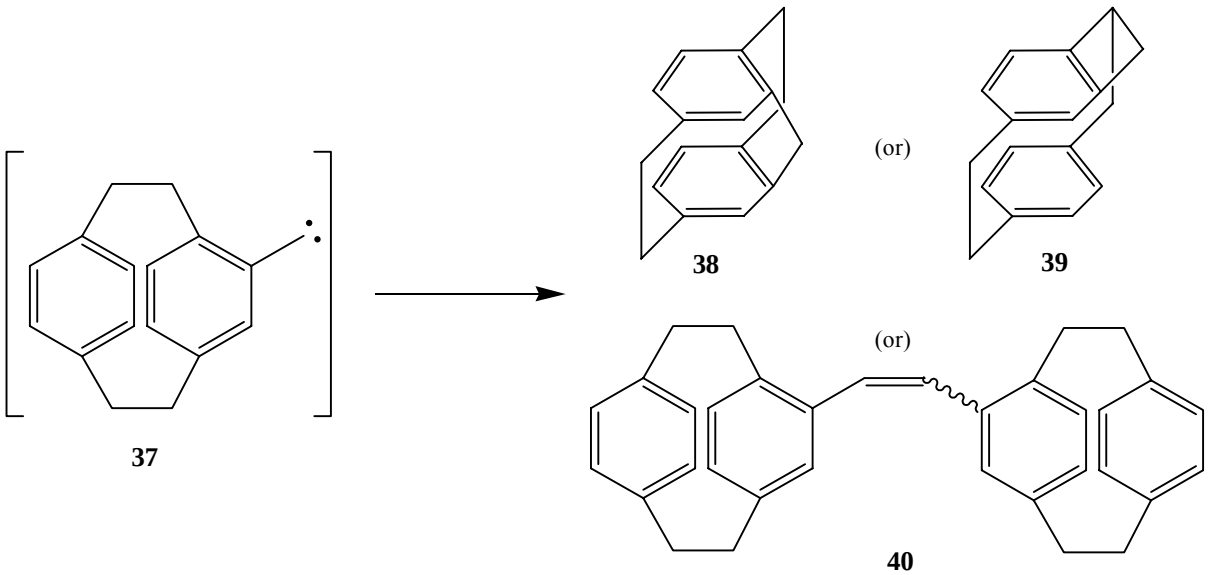
Scheme 15. New routes for indenonophanes.

1.4.5 *In situ* generated carbene – inter or intramolecular trapping?



37 **38** **39** **40**

Scheme 16. Trapping of a [2.2]paracyclophenyl carbene.

The application of [2.2]paracyclophane to mechanistic studies is shown in Scheme 16. Carbenes are highly reactive intermediates which play an important role in the formation of carbon bonds. They are normally generated *in situ*. When a reactive carbene intermediate like **37** is generated, it could undergo an intramolecular reaction to yield the highly strained molecules **38**/**39** and/or it could undergo intermolecular reaction (dimerisation) to give compound **40**. In the first alternative, ring expansion pathways are also conceivable; these would lead to novel [2.2]paracyclophane containing seven-membered rings as a subunit.

This compilation of the use of functionalised [2.2]paracyclophanes – to study the questions of stereochemistry, reactivity and applications for practical purposes – could easily be extended. It also illustrates that modern cyclophane chemistry is growing and is an interesting field even after nearly 60 years of the first description of this prototypical layered organic molecule.

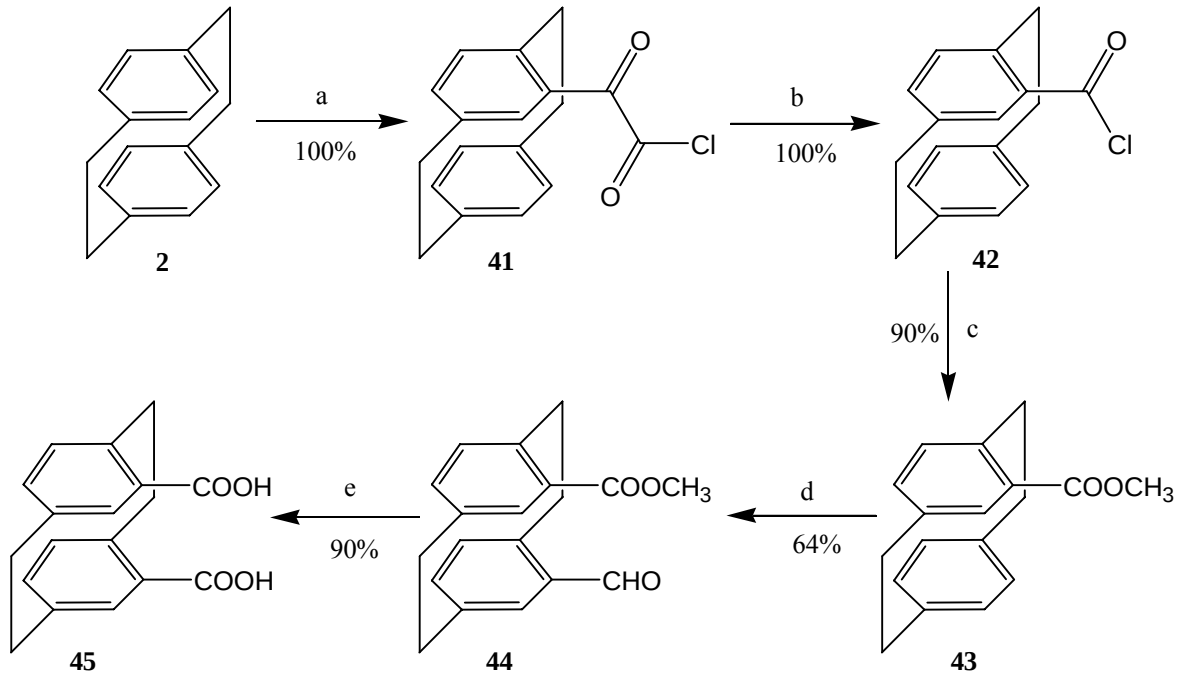
2. Results and discussion

2.1 Synthesis of *pseudo-geminal* dihalo[2.2]paracyclophanes

As discussed in the previous chapter the intramolecular directing effect can be made use of to obtain the basic *pseudo-geminal* or 4,15- substitution pattern specifically. Moreover, the synthesis of 4,15-diamino[2.2]paracyclophane (**49**) has been already accomplished.[20] Hence it was proposed to employ the diamine derivative as the starting material for further synthesis of the dihalo derivatives.

2.1.1 4,15-Diamino[2.2]paracyclophane (49)

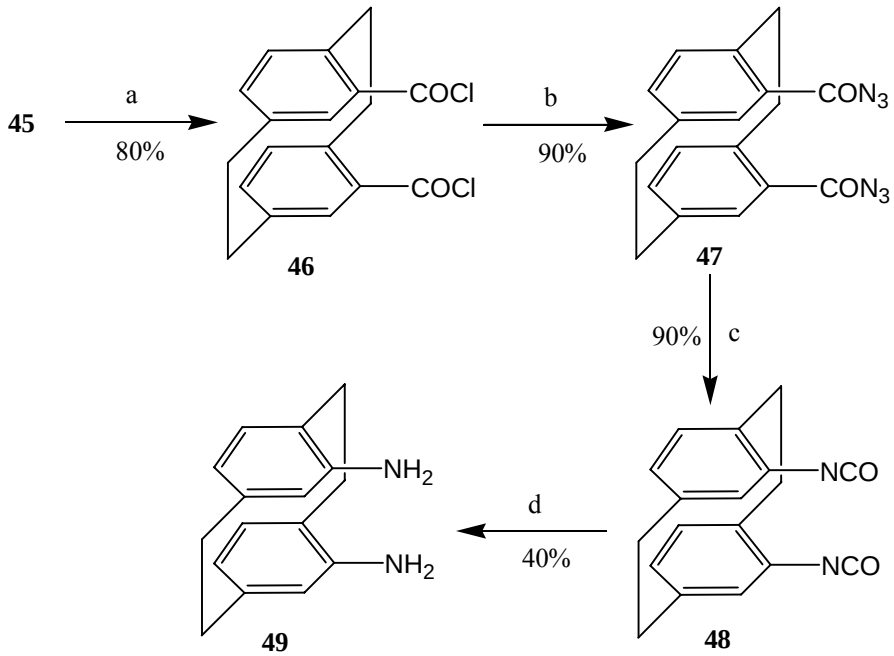
The synthesis of the diaminophane **49** was achieved in eight steps. Subjection of [2.2]paracyclophane (**2**) to Friedel-Crafts acylation using oxalylchloride in the presence of anhydrous $AlCl_3$ in dry dichloromethane under cold conditions yielded compound **41** quantitatively. This was then taken up in dry chlorobenzene and the solution refluxed over a period of 40 hours resulting in the expulsion of carbon monoxide to yield 4-chlorocarbonyl[2.2]paracyclophane (**42**) quantitatively.



a) $(COCl)_2/AlCl_3$, -5 °C; b) PhCl, Δ, 40 h; c) $MeOH/CH_2Cl_2$, Δ, 12 h; d) $TiCl_4/CH_3OCHCl_2$, -10 °C; e) (i) aq. KOH, Δ (ii) H_2O_2, 6 d, room temperature.

Scheme 17. Synthesis of 4,15-dicarboxy[2.2]paracyclophane (**45**).

As the chlorocarbonyl derivatives are unstable and are prone to react with moisture readily, dry and inert atmospheric conditions were maintained throughout the process and the compounds were used for further synthesis immediately. Treating **42** with dry methanol under reflux yielded 4-methoxycarbonyl[2.2]paracyclophane (**43**) in 90% yield as colourless crystalline solid after column chromatographic purification. In the ^{1}H NMR spectrum, the methyl group appears as a sharp singlet at δ = 3.89, being characteristic of the ester functionality. Compound **43** was subjected to Rieche formylation using titaniumtetrachloride and dichloromethylmethylether in dry CH_2Cl_2 as solvent under cold conditions to furnish 4-methoxycarbonyl-15-formyl[2.2]paracyclophane (**44**) in 64% yield. In this formylation reaction the intramolecular directing effect of the ester functionality guides the approaching electrophile in the *pseudo-geminal* position as described in Section 1.1. In the ^{1}H NMR spectrum, the formyl and the methyl ester groups appear as sharp singlets at δ = 9.9 and 3.8 respectively. Saponification of the methyl ester using aq. KOH under reflux and oxidation of the formyl group with 35% aq. H_2O_2 for six days at room temperature furnished 4,15-dicarboxy[2.2]paracyclophane (**45**) in 90% yield as colourless amorphous solid. (Scheme 17)



a) $SOCl_2$/DMF, Δ; b) acetone/aq. NaN_3, 0 °C; c) dry toluene, Δ; d) EtOH/aq. KOH, Δ, 45 h.

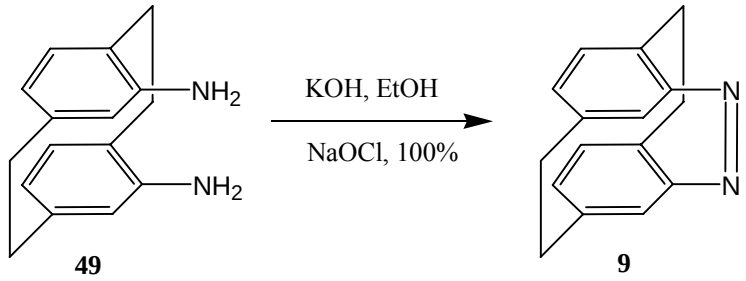
Scheme 18. Synthesis of 4,15-diamino[2.2]paracyclophane (**49**).

The diacid **45** was converted to its corresponding chlorocarbonyl derivative **46** in 80% yield by treatment with freshly distilled thionylchloride under reflux and catalysed by a drop of dry DMF. Compound **46** was subsequently converted to the corresponding azido derivative by

treating it with aq. NaN_3 in acetone under ice cold conditions to yield 4,15-bis(azidocarbonyl)[2.2]paracyclophane (**47**) quantitatively. In the IR spectrum strong absorption band corresponding to the azido group was observed at 2140 cm^{-1}. 4,15-Diisocyanato[2.2]paracyclophane (**48**) was obtained in 90% yield by the Curtius rearrangement of **47** under refluxing conditions in dry toluene under inert atmosphere. The diisocyanato-phane was converted to its diamine derivative by first converting to the corresponding bisurethane derivative in ethanol and on further treatment with aq. KOH under reflux, for 45 hours. This yielded 4,15-diamino[2.2]paracyclophane (**49**) as a brown solid in 40%.

2.1.2 4,15-Azo[2.2]paracyclophane (9)[11]

When 4,15-diamino[2.2]paracyclophane (**49**) was oxidized with sodium hypochlorite in ethanol at -8 °C in the presence of a base, the azo-bridged phane **9** was produced in 100% yield having a melting point of 235 °C. This triply bridged compound is the first example of a cyclophane, with a bridge consisting of heteroatoms only. At 150 °C and a pressure of 10^{-2} mbar, **9** sublimes to give yellow prism like crystals. The structure of the compound follows from the spectroscopic data and also from X-ray crystallographic analysis.[11] The main features of the structure are, the short diazo bridge with its N=N bond of 1.272 Å; the C–N bonds (1.474 and 1.467 Å) are slightly lengthened from the standard value of 1.431 Å.



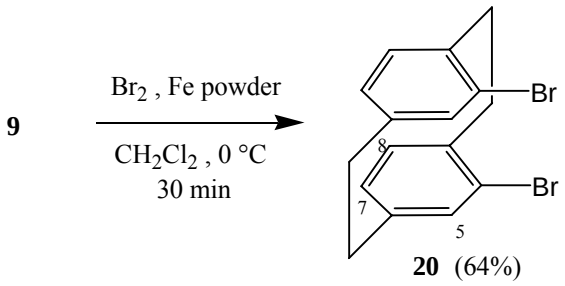
49 **9**

Scheme 19. Synthesis of 4,15-azo[2.2]paracyclophane (**9**).

2.1.3 4,15-Dibromo[2.2]paracyclophane (20)

When a solution of 4,15-azo[2.2]paracyclophane (**9**) in CH_2Cl_2 was treated with bromine under ice cold conditions in the presence of iron powder resulted in a remarkable substitution reaction where the nitrogen bridge was lost and the *pseudo-geminal*-dibromide **20** was

produced in good yield (Scheme 20). Crystallisation using $CHCl_3$/pentane mixture afforded colourless crystals of X-ray quality.



Scheme 20. Synthesis of 4,15-dibromo[2.2]paracyclophane (**20**).

The dibromo compound is of particular interest as in principle it should allow the preparation of dimeric organometallic reagents which could be useful for preparative purposes. The ^{1}H NMR spectrum of **20** shows a doublet at δ = 6.78 corresponding to 5-H with a *meta*-coupling constant of 1.37 Hz and another doublet at δ = 6.53 of that of 8-H with an *ortho*-coupling constant of 7.72 Hz. 7-H appears as a doublet of a doublet at δ = 6.50. In the ^{13}C NMR spectrum two peaks were observed at δ = 34.58 and 34.66 corresponding to the bridge carbon atoms and six peaks (δ = 140.8, 138.5, 135.6, 135.0, 132.3 and 125.1) corresponding to the aromatic carbon atoms.

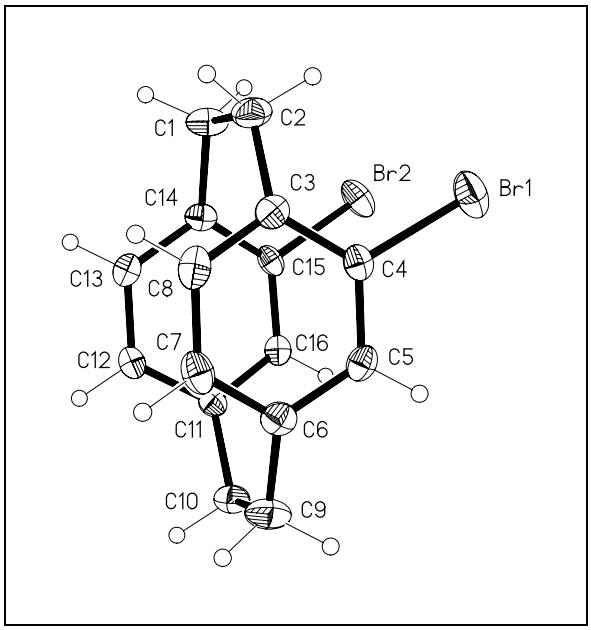
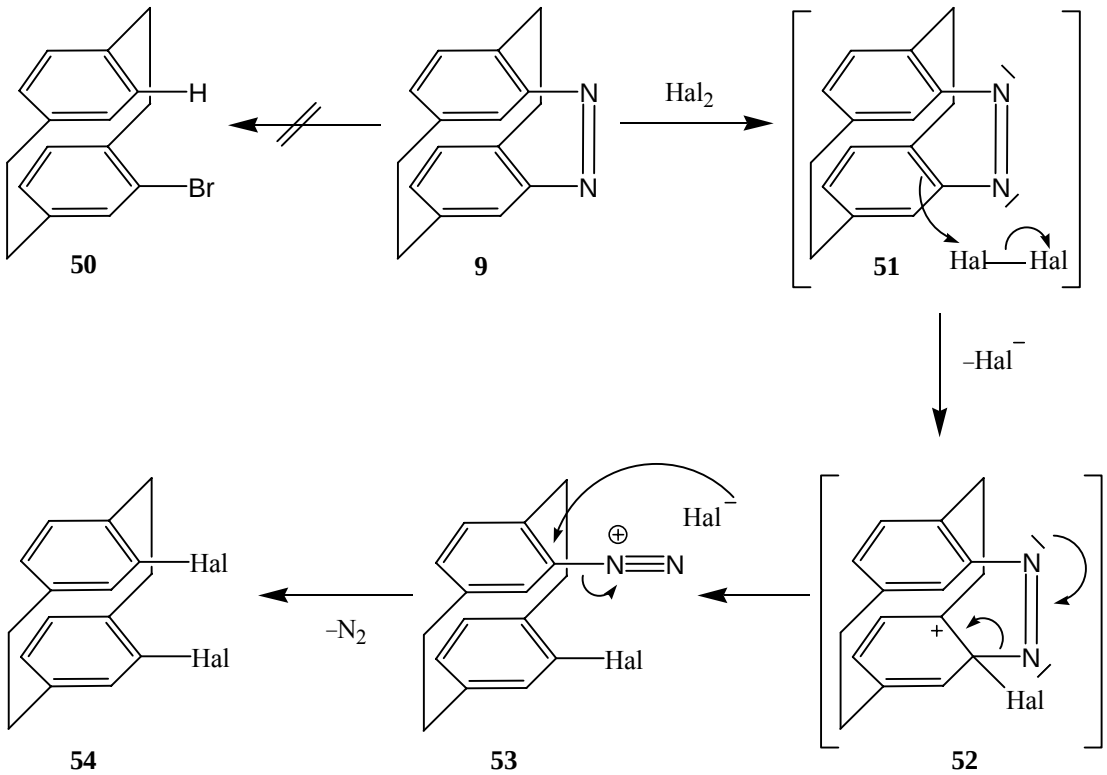


Fig. 1. Structure of 4,15-dibromo[2.2]paracyclophane (**20**) in the crystal.

The X-ray crystal analysis reveals that **20** crystallises with unit cells in $P2_1/n$ (monoclinic) and displays the general structural features of [2.2]paracyclophane such as the flattened boat configuration of the rings and the lengthened C–C single bonds in the bridges (1.576–1.589 Å). The intramolecular Br...Br distance being 3.6747(5) Å. Also weak intermolecular hydrogen bonding [C12–H12...Br1, 2.79 Å] and halogen-halogen interactions [Br1...Br2 (3.8072 Å), Br1...Br1 (3.6223 Å)] between molecules were observed.

To understand the mechanism of the deazotization process, the reaction was carried out at low temperature (-50 °C) hoping to trap an intermediate, while the reaction was followed by TLC. Till -10 °C the starting materials remained unreacted and by the time the temperature rose to 0 °C all the azophane was converted to dibromophane **20**. Hence another alternative strategy was adopted by treating the azophane **9** under icecold conditions with HBr and acetic acid expecting to give the monobromide **50**. When HBr was added to the reaction mixture, it turned readily into reddish brown solution which after the normal workup gave only an intractable material.

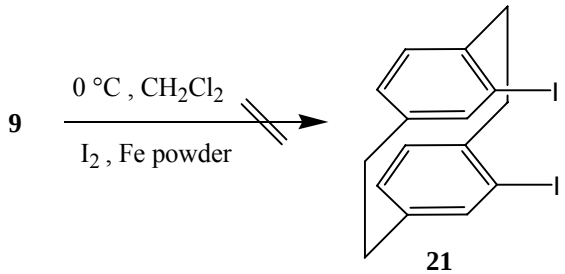


Scheme 21. General mechanism of deazotization of **9**.

The deazotization process is proposed to begin with an *ipso* attack at the heteroatom bridge, providing the σ–complex **52**. The complex rearomatizes by forming the diazonium salt **53**. In the last step, the halide attacks again at the *ipso* position resulting in the formation of the *pseudo-geminal*-dihalide **54** under expulsion of N_2 (Scheme 21).

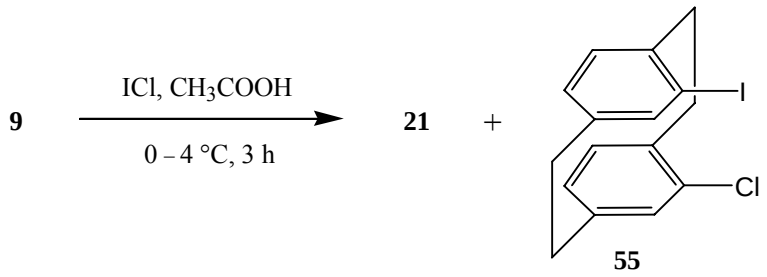
2.1.4 4,15-Diiodo[2.2]paracyclophane (21)

Following the successful synthesis of the dibromophane **20**, a similar synthetic strategy was sought for the synthesis of 4,15-diiodo[2.2]paracyclophane (**21**). Azophane **9** was subjected to iodine treatment in the presence of iron powder in dry dichloromethane under ice cold conditions. Thin layer chromatographic (TLC) analysis revealed only the presence of the starting material. The reaction mixture was further allowed to stir at room temperature for 2 days but no characteristic reaction took place. Finally treatment with a catalytic amount of trifluoroacetic acid also resulted only in the recovery of the starting material.



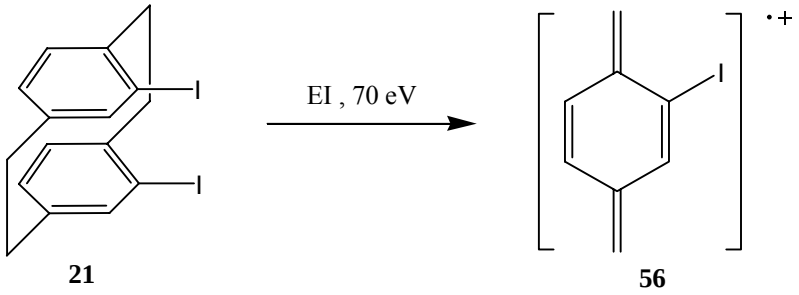
Scheme 22. Attempted synthesis of **21**.

Synthesis of **21** was however achieved by replacing iodine with iodine monochloride (ICl) and using glacial acetic acid as solvent. A solution of **9** in glacial acetic acid under ice cold conditions (0–4 °C), upon treatment with ICl over a period of 3 hours, resulted in the desired 4,15-diiodo[2.2]paracyclophane (**21**) as a colourless solid in 22% yield (Scheme 23). Also trace amounts of 4-chloro-15-iodo[2.2]paracyclophane (**55**) were formed. The mass spectrum show peaks at m/z = 138.4 and 230 characteristic of the two "halves" of **55**. As far as the mechanism is concerned, it is suggested to be similar to that of the formation of the dibromophane **20** (Scheme 21). It could be that first compound **55** is formed which further undergoes interhalogen substitution reaction in which the chlorine substituent is subsequently replaced by iodine. Compound **55** was detected only in the mass spectrometry and could not be isolated.



Scheme 23. Synthesis of 4,15-diiodo[2.2]paracyclophane (**21**).

Attempts to prepare and isolate **55** by varying the concentrations of the azophane **9** and ICl met with failure and every time only the diiodophane **21** was isolated. In the ^{1}H NMR spectrum, the 5-H of compound **21** is shifted by approximately 0.3 ppm to lower fields as compared to the corresponding dibromo derivative **20**. In the mass spectrum the breaking of the molecule into two halves **56**, *m*/*z* = 230 (Scheme 24) could be seen clearly and forms the base peak, being characteristic of [2.2]paracyclophane molecules.



Scheme 24. Fragmentation of **21** in the mass spectrometer.

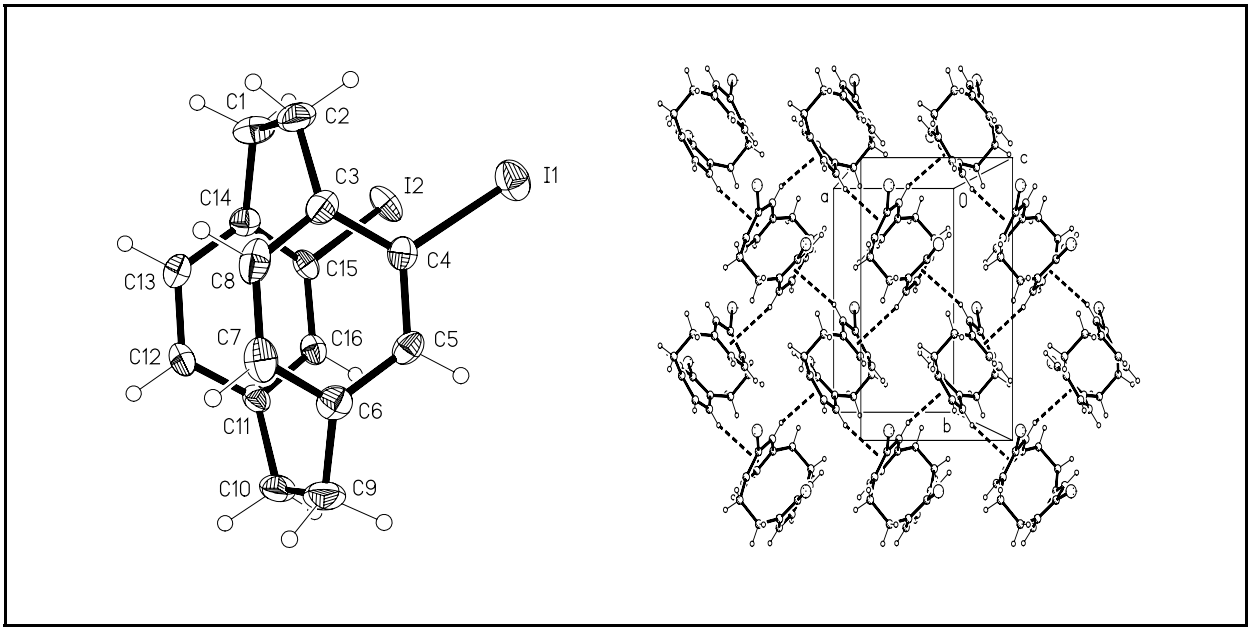
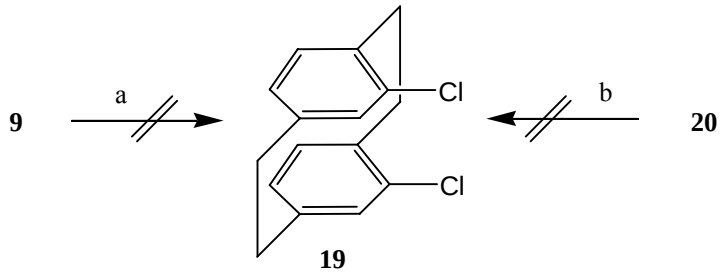


Fig. 2. Crystal structure and packing diagram of 4,15-diiodo[2.2]paracyclophane (**21**).

Colourless prism-shaped single crystals of **21** for X-ray analysis were obtained from dichloromethane/pentane by the slow diffusion method. Like the bromophane **20**, iodophane **21** crystallises in $P2_1/n$ (monoclinic) unit cell, the packing of the molecules is also similar. The intramolecular halogen-halogen [I…I] distance was found to be 3.961(2) Å. If this was sterically unfavourable, one would expect some strain to be noticeable in terms of lengthening of bridge bonds and bending of the aromatic carbons. Also intermolecular hydrogen bonding [C(12)-H(12)...I(1), 3.08 Å] and interhalogen interactions between molecules could be seen.

2.1.5 4,15-Dichloro[2.2]paracyclophane (19)

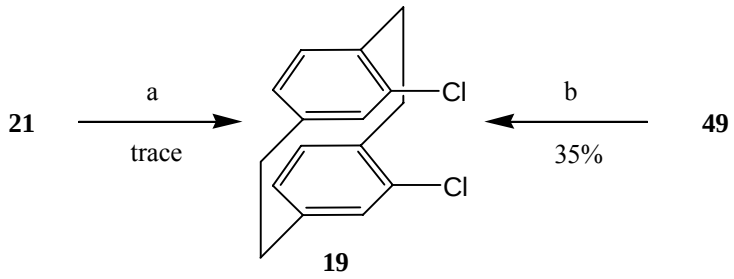
After the successful synthesis of the dibromo and diiodo phanes from **9** a similar methodology was adopted to realise **19**. A solution of the azophane **9** in dry dichloromethane was treated with a solution of chlorine gas dissolved in dry dichloromethane under ice cold conditions in the presence of anhydrous $FeCl_3$ as catalyst. However, this resulted in the loss of starting material and no desired product was obtained. In 1969, Watanabe *et al.* have successfully carried out halogen exchange reactions of haloferrocenes using copper(I) salts.[51] Following this protocol 4,15-dibromophane (**20**) was treated with pyridine and anhydrous CuCl and the suspension was heated to 130 °C for 5 hours under inert atmosphere. Unfortunately only intractable material was produced (Scheme 25).



a) Cl_2(g), anhydrous $FeCl_3$, CH_2Cl_2, 0 °C; b) pyridine, anhydrous CuCl, 130 °C.

Scheme 25. Attempted synthesis of 4,15-dichloro[2.2]paracyclophane (**19**).

An alternative way of performing halogen exchange is by means of a photochemical method. Photochemical interhalogen conversion of aromatic chloro compounds from aromatic iodo compounds has been carried out by Taylor *et al.*[52] When diiodophane **21** was irradiated with light (normal white light, 120 W), in the presence of CCl_4 as solvent, trace amounts of **19** were generated as detected by mass spectrometry. Finally, **19** was realised in reasonable yields by the classical diazotisation methodology.



a) hυ, CCl_4; b) $NaNO_2$, conc. HCl, CuCl, 0 °C → room temperature → 70 °C.

Scheme 26. Synthesis of 4,15-dichloro[2.2]paracyclophane (**19**).

Compound **49** was diazotised using the standard procedure ($NaNO_2$, conc. HCl) under cold conditions. The diazonium salt solution so produced, was treated with an acidic solution of CuCl and the mixture was heated to 70 °C for 30 minutes.[21] Column chromatographic purification of the crude product on silica gel furnished the desired 4,15-dichloro[2.2]paracyclophane (**19**) in 35% yield. Colourless tablet-like crystals for X-ray analysis were obtained by the slow diffusion crystallisation method using chloroform/pentane mixture. **19** also crystallises with similar unit cells ($P2_1/n$, monoclinic) as the other halo derivatives, but the crystal packing is different. The packing consists of layers with a herring bone pattern. Also, strikingly, there are short intermolecular contacts [C16-H16…Cg (C4, 5, 7, 8), 2.50 Å; C2-H2B…Cg (C12, 13, 15, 16), 2.63 Å] from hydrogen atoms to the centroids of the rings.

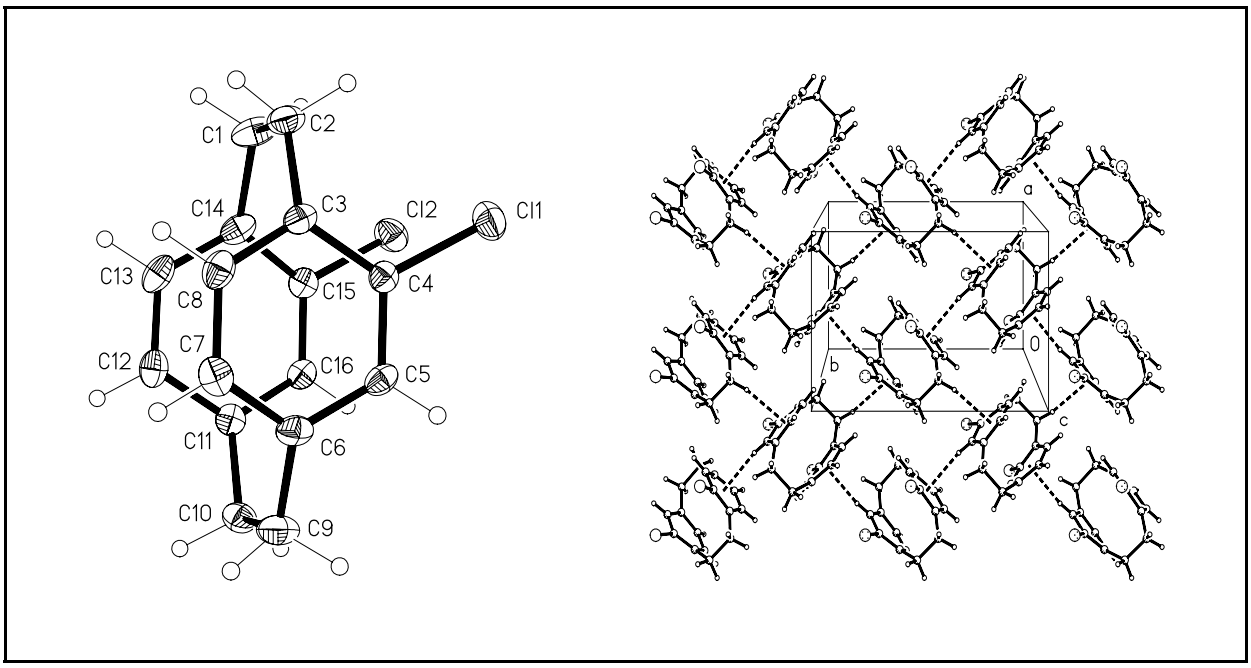
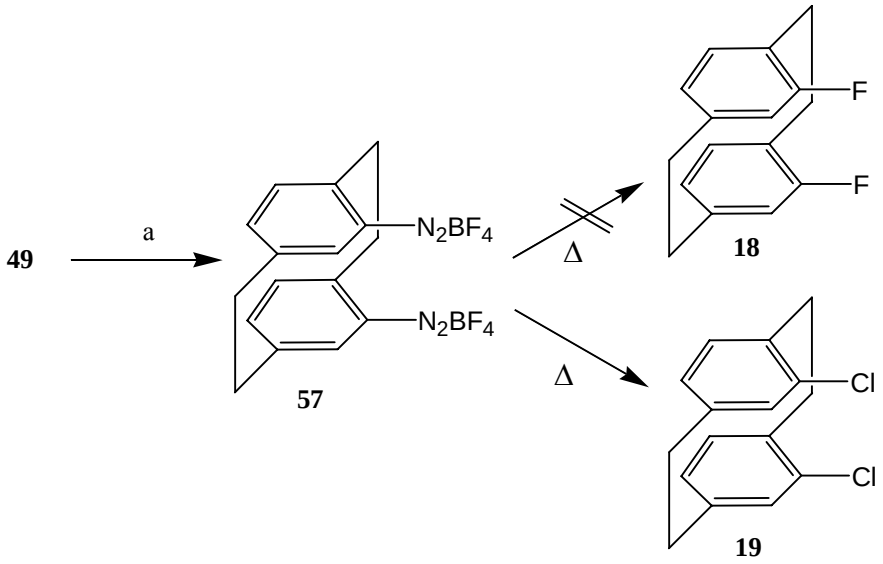


Fig. 3. Crystal structure and packing diagram of 4,15-dichloro[2.2]paracyclophane (**19**).

2.1.6 4,15-Difluoro[2.2]paracyclophane (18)

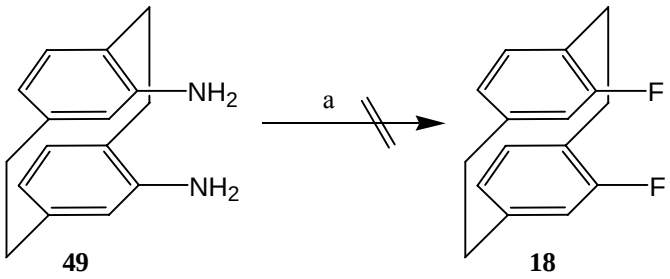
One of the best ways of introducing fluorine into an aromatic ring is by the classical Balz–Schiemann reaction. The fluorine is introduced by the decomposition of the corresponding diazonium fluoroborate salt. The fluoroborate salt **57** was prepared by the usual diazotisation of the corresponding diamine **49** using conc. HCl and aq. $NaNO_2$ under ice cold conditions. Subsequently the mixture was added to an ice cold aq. $NaBF_4$ solution resulting in the precipitation of **57**. The precipitate was dried and the salt was heated in the dry state. Column chromatographic purification and analysis of the compound revealed the formation of *pseudo-geminal*-dichloro[2.2]paracyclophane (**19**) instead of the difluoro derivative. A slight modification of the reaction was carried out by changing the acidic medium to conc. sulfuric acid instead of hydrochloric acid, but this also resulted only in trace formation of **19**.



a) conc. HCl, aq. $NaNO_2$, aq. $NaBF_4$, 0 °C.

Scheme 27. Attempted synthesis of 4,15-difluoro[2.2]paracyclophane (**18**) by Balz–Schiemann reaction.

Hence an alternative preparative methodology was adopted which was similar to that of the synthesis of 4-fluoro[2.2]paracyclophane.[22] The preparation involves the addition of 4,15-diamino[2.2]paracyclophane (**49**) under cold conditions and inert atmosphere to a cooled suspension of nitrosyl tetrafluoroborate in dry xylene. The mixture was allowed to warm to room temperature and then subjected to reflux for 30 minutes. Treatment of the resulting reaction mixture with 2N aq. sodium hydroxide solution under reflux resulted in a dark brown intractable material (Scheme 28).



49 **18**

a) (i)$NOBF_4$, dry xylene, -2 °C → room temperature → reflux, 30 min; (ii) 2N aq. NaOH, reflux, 15 min.

Scheme 28. Attempted synthesis of 4,15-difluoro[2.2]paracyclophane (**18**).

As already mentioned the synthesis of the mixture of four isomers of difluoro[2.2]paracyclophane was accomplished, by converting the mixture of isomers (in the ratio 1:1:1:1) of difluoro-2,11-dithia[3.3]paracyclophane to the corresponding bissulphones and on subsequent pyrolysis yields the difluorophane isomers in the ratio 3(*meta*):2(*ortho*):2(*para*):1(*geminal*), by Ernst *et al.*[17] A sample of the mixture of isomers was obtained from Prof. Ernst and the *pseudo-geminal*-isomer **18** was successfully isolated by preparative thin layer chromatography using 1:20 dichloromethane/pentane mixture. Compound **18** separates very clearly as the lowermost band after several runs. The $J_{F\text{-}F}$ coupling was found to be 13.8 Hz.

A summary of the ^{1}H NMR chemical shifts of all *pseudo-geminal*-dihalo[2.2]paracyclophane isomers is given in Table 1. As the size of the halogen atom increases the 5-H is shifted to lower fields by a maximum of 0.9 ppm. Also the 7-H shows appreciable shift to the lower field (~0.2 ppm) and very small low field shift is exhibited by the 8-H. The bridge hydrogen atom on the *anti* position (1-H*a*) also exhibits appreciable low field shifts by a maximum of ~0.4 ppm.

	18	**19**	**20**	**21**
δ(1-H*a*)	2.76	2.96	3.03	3.15
δ(1-H*s*)	3.54	3.74	3.72	3.60
δ(5-H)	6.17	6.57	6.79	7.07
δ(7-H)	6.38	6.48	6.51	6.55
δ(8-H)	6.44	6.54	6.53	6.50
δ(9-H*a*)	3.05[a]	3.05	3.04	3.04
δ(9-H*s*)	3.02[a]	2.99	2.98	2.97

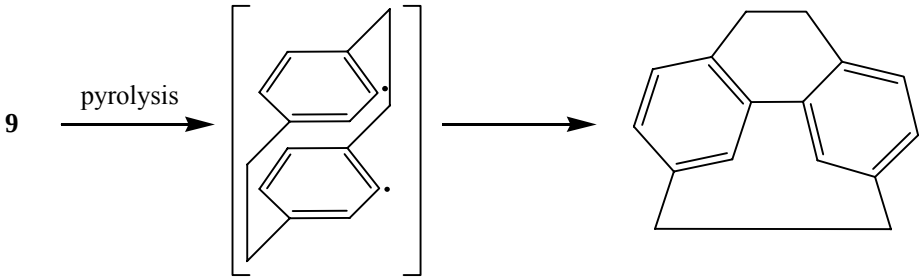
[a] Assignments are interchangeable; *a*-anti; *s*-syn.

Table 1. ^{1}H NMR chemical shifts of **18**–**21** in $CDCl_3$.

The halo derivatives **19**, **20** and **21**, from their crystal structure, display general features of [2.2]paracyclophanes, such as the flattened boat configuration of the rings and the lengthened C–C single bonds in the bridges (1.576 – 1.589 Å). Two effects of the halogen substituents are: first, the reduced ring angles (C4–C3–C8) at the *ortho* bridgehead carbon atoms to ca. 115°, whereas the corresponding *meta* angles (C5–C6–C7) remain at the typical cyclophane value of ca. 117°; and secondly, the widened C–C–C angles from the substituent to the bridge (e.g., C4–C3–C2) to 123 – 124°, presumably by the steric interactions with the bridge hydrogen atoms.

2.1.7 Pyrolysis of 4,15-azo[2.2]paracyclophane (9)

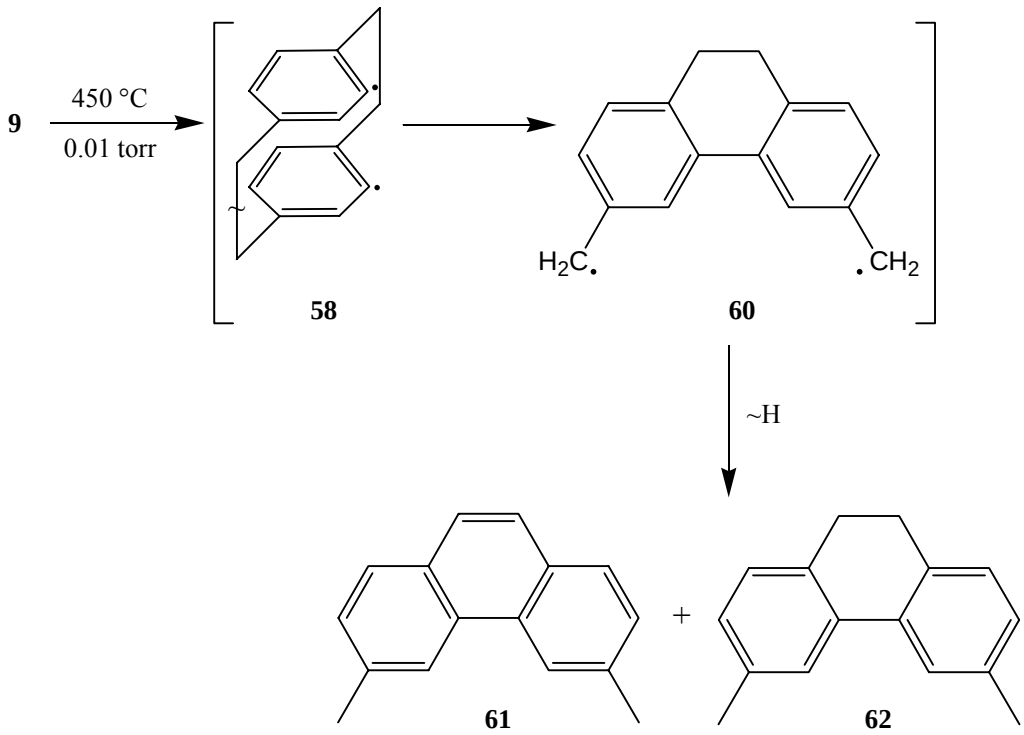
The pyrolysis of aliphatic and aromatic azo compounds has been thoroughly investigated.[23] Thermolysis of azo compounds results in the cleavage of the C-N bond yielding a nitrogen molecule and two radicals. Hence they are most convenient sources of radicals and biradicals of any desired structure. Subjection of the azophane **9** to high temperature pyrolysis could also lead to the loss of nitrogen, resulting in the formation of an unstable biradical intermediate **58**, which can lead to the formation of a zero bridge between the two benzene rings giving rise to the highly strained compound **59** (Scheme 29). Clearly, with a calculated strain energy of 123 kcal/mol (relative to [2.2]paracyclophane, MMX force filed programme) one would not expect this compound to survive under the reaction condition.



Scheme 29. Proposed generation of the strained molecule **59** from 4,15-azo[2.2]para-cyclophane (**9**).

Subjecting **9** to flash vacuum pyrolysis at 450 °C - the compound was found to be stable and begins to decompose only at this temperature - at a pressure of 0.01 torr, resulted in the formation of two defined products in trace quantities. Spectroscopic analysis revealed the compounds to be 3,6-dimethylphenanthrene[56] (**61**) and 3,6-dimethyl-9,10-

dihydrophenanthrene[57] (**62**). The formation of these aromatic hydrocarbons may be explained by the generation of the diradical **58** by the loss of nitrogen, a deazotization process which presumably takes place in stepwise manner. This intermediate could undergo bridge rupture while simultaneously generating the prerequisite for radical recombination. The double benzylic radical **60** thus produced can stabilise itself either by a formal intramolecular hydrogen-transfer process, furnishing **61**, or by intermolecular hydrogen transfer to give **62**.



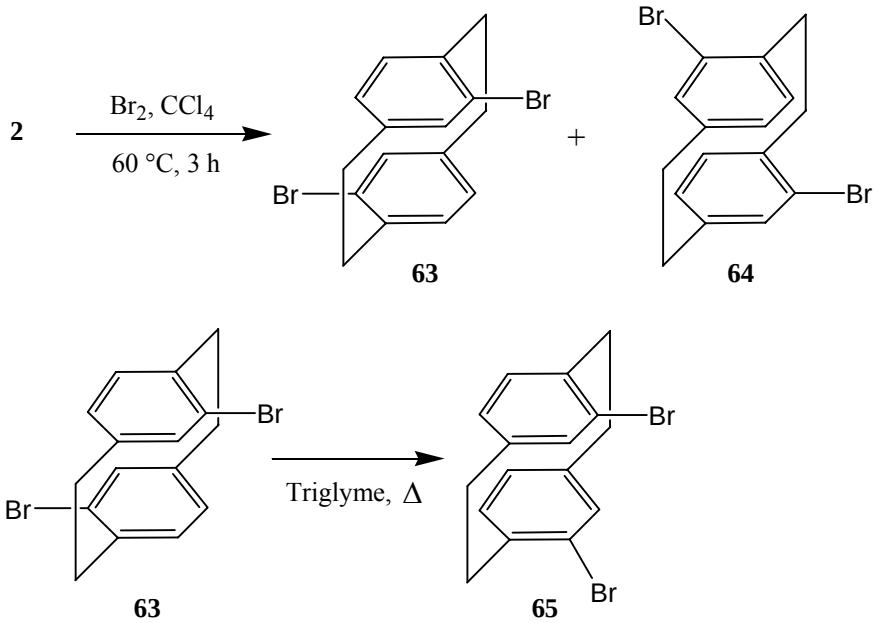
Scheme 30. Flash vacuum pyrolysis of the azophane **9**.

2.2 Synthesis and reactions of *pseudo-ortho*-diisocyanato[2.2]paracyclophane (22)

The synthetic sequence adopted to synthesise **22** was similar to that of the synthesis of the *pseudo-geminal*-diisocyanato[2.2]paracyclophane. Retrosynthetic analysis reveals that the isocyanate could be realised from the corresponding azidocarbonyl derivative, by Curtius rearrangement, which in turn from the corresponding acid derivative. The synthesis of *pseudo-ortho*-dicarboxy[2.2]paracyclophane (**67**) has already been accomplished[24] from the corresponding dibromo derivative.

2.2.1 4,16-Dicarboxy[2.2]paracyclophane (67)

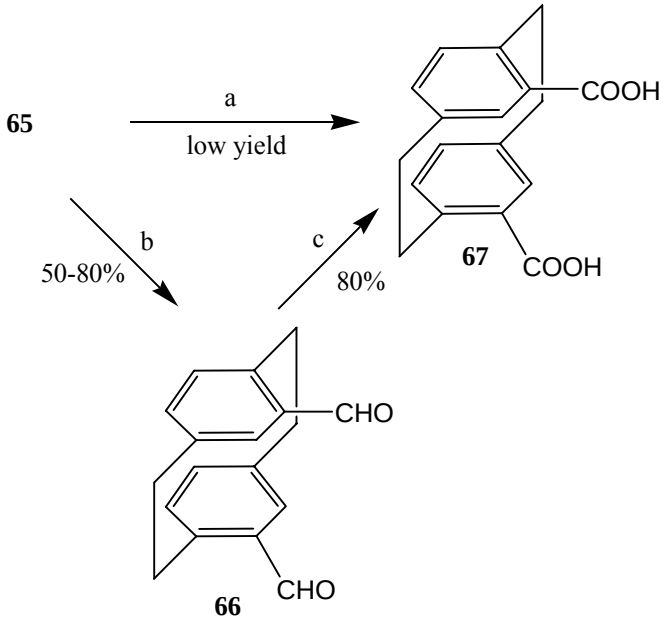
Bromination of [2.2]paracyclophane (**2**) at 60 °C using a sixfold excess of bromine in an inert solvent like CCl_4 over a period of three hours produces two isomers of dibrominated [2.2]paracyclophane, namely the *pseudo-para*-dibromo[2.2]paracyclophane (**63**) and *pseudo-meta*-dibromo[2.2]paracyclophane (**64**). Thermal isomerisation of the *para* isomer **63** in triglyme (b.p. 216 °C) resulted in the formation of *pseudo-ortho*-dibromo[2.2]paracyclophane (**65**)[25] (Scheme 31). A convenient and easy method was found for the isolation of compound **65** from triglyme. The reaction mixture was cooled in an ice bath and water was added slowly to it with stirring. Approximately 15 mL of ethanol was also added. Allowing this mixture to stand over a period of time under icecold condition resulted in the precipitation of **65** as off-white solid which was further purified by column chromatography on silica gel.



Scheme 31. Bromination of [2.2]paracyclophane (**2**) and thermal isomerisation reaction of the resulting dibromide **63**.

Lithiation of **65** using *n*-BuLi in dry ether and further treatment with solid carbondioxide (dry ice) according to the procedure of Rozenberg *et al.*[24] yielded the dicarboxy derivative **67** in very poor yields. Hence an alternative route was adopted by first converting the dibromo to the diformyl derivative **66**, which was further oxidised to the diacid **67**. Subjection of compound **65** to dilithiation using *n*-BuLi in dry ether and further treatment with *N*-formylpiperidine produced 4,16-diformyl[2.2]paracyclophane (**66**) as a pale yellow solid. The yields of this reaction varied from 50–80%. In the IR spectrum the carbonyl group shows a

strong absorption band at 1680 cm^{-1}. In the mass spectrum, the molecule splits into two halves (*m/z* = 132, 95%), and the loss of a carbonyl moiety (*m/z* = 104, 100%) could also be observed. In the ^{1}H NMR spectrum the formyl proton appears as a sharp singlet at δ = 9.8 and in the ^{13}C NMR spectrum the carbonyl carbon absorbs at δ = 191.9. Compound **66** was oxidised to 4,16-dicarboxy[2.2]paracyclophane (**67**) in 80% yield by using sodium chlorite in the presence of aq. sodium dihydrogen phosphate as buffering agent and *t*-butanol as solvent.[26, 53] 2-Methyl-2-butene was used as a scavenger to eliminate various unwanted positive chlorine species present.



a) *n*-BuLi, dry ice, ether, conc. HCl, H_2O; b) *n*-BuLi, *N*-formyl piperidine, room temperature, ether; c) aq. $NaH_2PO_4.H_2O$, aq. $NaClO_2$, *t*-BuOH, 2-methyl-2-butene, H_2O, room temperature.

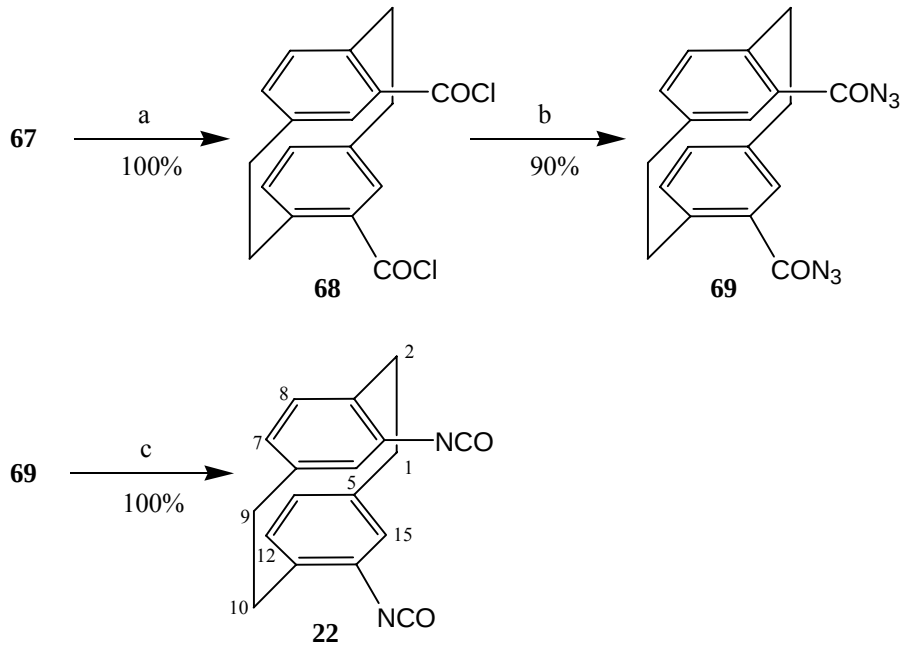
Scheme 32. Synthesis of 4,16-dicarboxy[2.2]paracyclophane (**67**).

2.2.2 4,16-Diisocyanato[2.2]paracyclophane (22)

The *pseudo-ortho*-dicarboxy derivative **67** thus obtained, as already discussed above, was treated with thionylchloride in the presence of trace amounts of DMF as a catalyst, under reflux conditions, yielding the corresponding bis(chlorocarbonyl) derivative **68**. The same conversion was also carried out by an alternate method developed by Rebek, which employs milder reaction conditions.[27] Treatment of **67** with oxalylchloride in dry dichloromethane, catalysed by a drop of 10% v/v mixture of DMF/dichloromethane at room temperature yielded 4,16-bis(chlorocarbonyl)[2.2]paracyclophane (**68**) quantitatively. In the ^{1}H NMR spectrum, 5-H appears as a doublet at δ = 6.95 with a small *meta* coupling constant of 1.4 Hz.

The signals for 7-H and 8-H overlap with each other and, more interestingly, also exhibit very small *meta* and *ortho* coupling constants of 1.5 Hz and 6.2 Hz, respectively.

Subjection of **68** to nucleophilic substitution using aq. sodium azide under ice cold conditions produced 4,16-bis(azidocarbonyl)[2.2]paracyclophane (**69**) as a pale yellow amorphous solid in 90% yield. In comparison to **68**, the ^{1}H NMR spectrum of **69** is well resolved and also shifted more strongly to lower fields. 5-H is shifted downfield by approximately 0.21 ppm compared to the signal of the chlorocarbonyl derivative **68**. In the IR spectrum, strong absorption bands were observed at 2141 and 1680 cm^{-1} corresponding to the azide and carbonyl groups, respectively. Column chromatographic purification on silica gel resulted in the decomposition of **69** to give 4,16-diisocyanato[2.2]paracyclophane (**22**) in trace quantities.



a) $(COCl)_2$, a drop of 10% v/v DMF/CH_2Cl_2, room temp.; b) aq. NaN_3, acetone, 0 °C; c) dry toluene, reflux.

Scheme 33. Synthesis of 4,16-diisocyanato[2.2]paracyclophane (**22**).

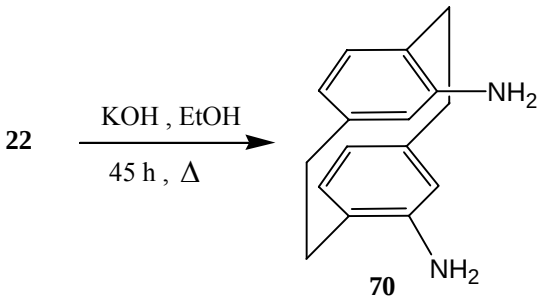
Hence the crude **69** was used without further purification for the Curtius rearrangement reaction in refluxing anhydrous toluene to give **22** quantitatively. During the course of the rearrangement reaction, as the temperature of the reaction mixture reaches about 95 °C, the evolution of nitrogen gas could be seen clearly. The reaction was subjected to extended reflux to ensure completion of the rearrangement. In the IR spectrum, the isocyanate displays a strong absorption band at 2296 cm^{-1}. The ^{1}H NMR spectrum of **22** is shifted to higher field compared to its precursors. 5-H appears at δ = 6.49 which is approximately 0.7 ppm upfield as

compared to the bis(azidocarbonyl) isomer. A comparison of these chemical shift values of the aromatic protons of **68**, **69** and **22** is summarized in Table 2.

	68	**69**	**22**
δ(5-H)	6.95	7.16	6.49
δ(7-H)	6.66	6.78	6.40
δ(8-H)	6.63	6.59	6.51

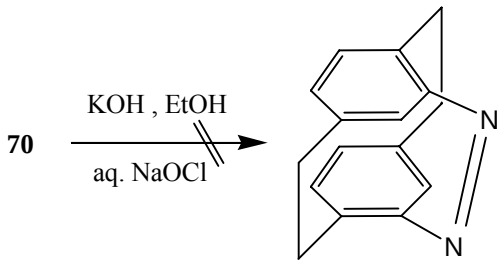
Table 2. Selected ^{1}H NMR chemical shifts of **68**, **69**, and **22** in $CDCl_3$.

2.2.3 4,16-Diamino[2.2]paracyclophane (70)



Scheme 34. Synthesis of 4,16-diamino[2.2]paracyclophane (**70**).

Compound **70** was obtained quantitatively as a pale brown solid by converting **22** to its bisurethane derivative by refluxing it in ethanol and further treatment of this intermediate with 20% aq. KOH solution also under reflux conditions. The above synthetic procedure is similar to that employed for the synthesis of the *pseudo-geminal*-diamino[2.2]paracyclophane (**49**) described above (Section 2.1.1). The amine protons of **70** appear as a broad singlet at δ = 3.32 in the ^{1}H NMR spectrum. Subjecting the amine **70** to oxidation using aq. NaOCl and ethanolic KOH solution to yield 4,16-azo[2.2]paracyclophane (**71**) failed (Scheme 35). Synthesis of **71** was of interest as it would be the first example of *pseudo-ortho* bridged cyclophane. The failure of the reaction may be attributed to the fact that the amino functionalities are too far apart from each other to allow ring closure.



70 **71**

Scheme 35. Attempted synthesis of 4,16-azo[2.2]paracyclophane (**71**), a chiral azo compound.

Density functional theory calculations of **70** using the B3LYP/6-31G(d) programme show indeed that the amino groups are 4.23 Å apart from each other, which is a large distance compared to the N=N distance (1.272 Å) in azophane **9**.

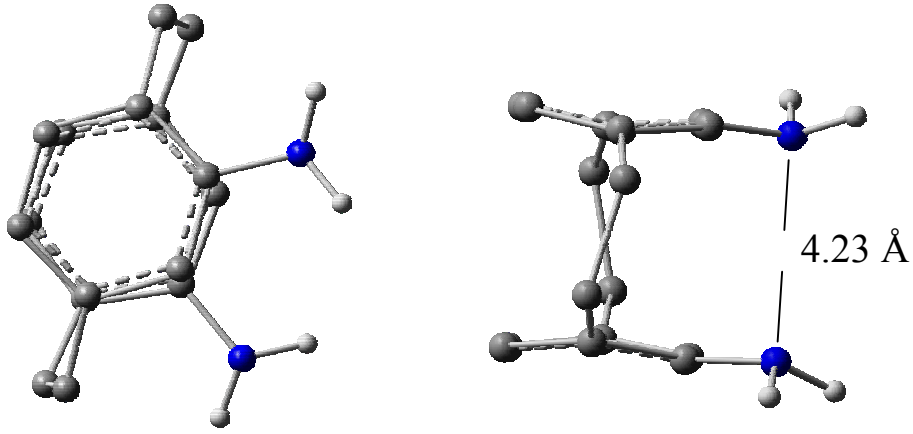
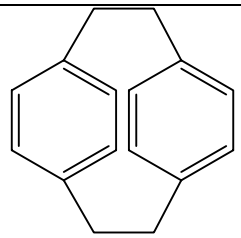
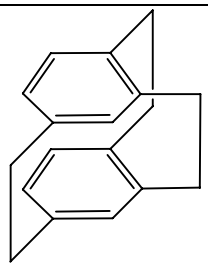
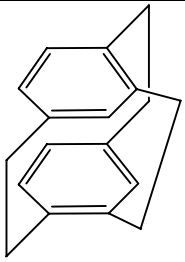
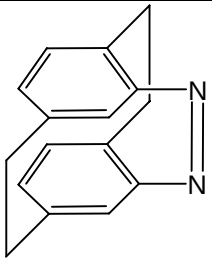
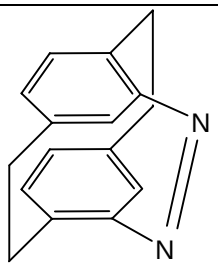


Fig. 4. Structure of **70** according to B3LYP/6-31G(d) calculations.

Also the strain energy calculated using the MMX force field programme clearly shows that *pseudo-ortho*-azo[2.2]paracyclophane (**71**) has a relative strain energy of 99.8 kcal/mol compared to [2.2]paracyclophane, which is very high. As a matter of fact, **71** is higher in strain energy by 74 kcal/mol than its corresponding carbon analogue **73**. Hence, though **71** could be thermodynamically stable, realising such strained molecule under the above discussed reaction conditions is not possible. The table below summarises the heat of formation, strain energy and relative strain energy of various molecules calculated.

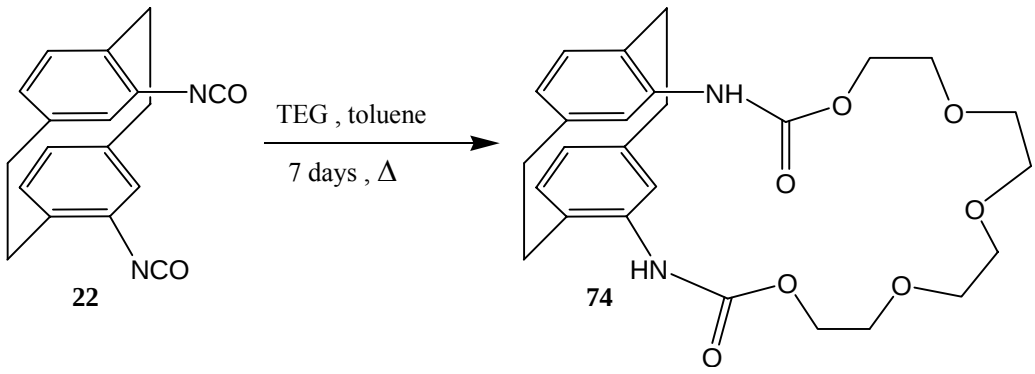
	rel. SE [kcal/mol]	SE [kcal/mol]	H_f [kcal/mol]
 **2**	0.0	49.9	60.7
 **72**	14.2	64.1	69.2
 **73**	25.8	75.7	81.5
 **9**	62.2	112.1	224.9
 **71**	99.8	149.7	263.9

Strain energy (SE) [kcal/mol], Heat of formation (H_f) [kcal/mol].

Table 3. Calculated strain energy and enthalpy of formation of *pseudo-geminal* and *pseudo-ortho* bridged [2.2]paracyclophanes using the MMX force field programme.

2.2.4 *Pseudo-ortho*-crownophane (74)

As already mentioned, *pseudo-ortho*-functionalised cyclophanes are chiral in nature. Hence it was envisaged to synthesise chiral crownophanes which may find applications in chiral synthesis. *Pseudo-geminal* substituted crownophanes (achiral) have already been synthesised by Zitt[28] starting from the corresponding 4,15-diisocyanato[2.2]paracyclophane (**48**) and also a few complexation properties of similar crownophanes have been studied by Hillmer.[53] Treatment of 4,16-diisocyanato[2.2]paracyclophane (**22**) under reflux and high dilution conditions with tetraethylene glycol (TEG) in anhydrous toluene for seven days produced the crownophane (**74**) in 68% yield as a colourless crystalline solid after purification by column chromatography on silica gel (Scheme 36).



Scheme 36. Synthesis of crownophane (**74**).

In the ^{1}H NMR spectrum, the NH protons appear as a broad singlet at δ = 7.35 which is approximately 0.3 ppm downfield from that of the corresponding *pseudo-geminal*-crownophane.[28] Broad peaks at δ = 4.16 and 4.63 corresponding to four protons were assigned to 21-H and 31-H and the remaining 12 protons of the crown part appear as multiplet in the region δ = 3.62–3.82. In the IR spectrum, strong absorption band due to the C=O moiety was observed at 1738 and 1637 cm^{-1}. Interestingly the *pseudo-geminal*-crownophane melts at 120 °C[28] whereas **74** melts at 176 °C, a pronounced 56 °C increase caused by small change in the substitution pattern. The enantiomers of the chiral crownophane **74** were separated successfully using chiral HPLC and the details are discussed in the Section 2.2.9.

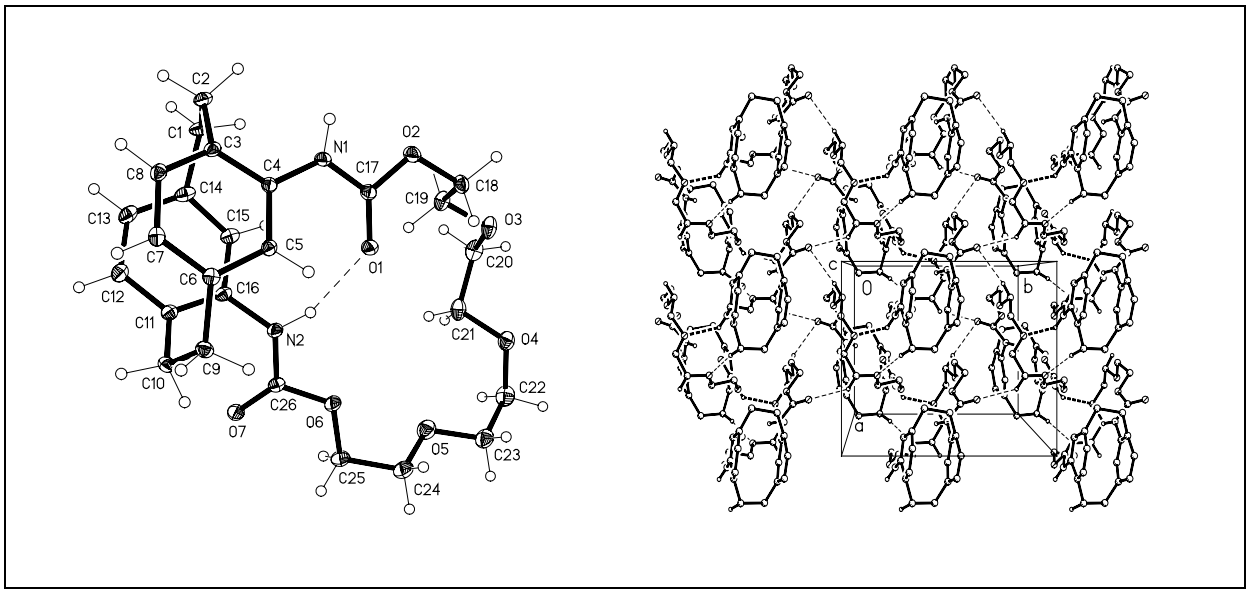


Fig. 5. Crystal structure and packing diagram of **74**.

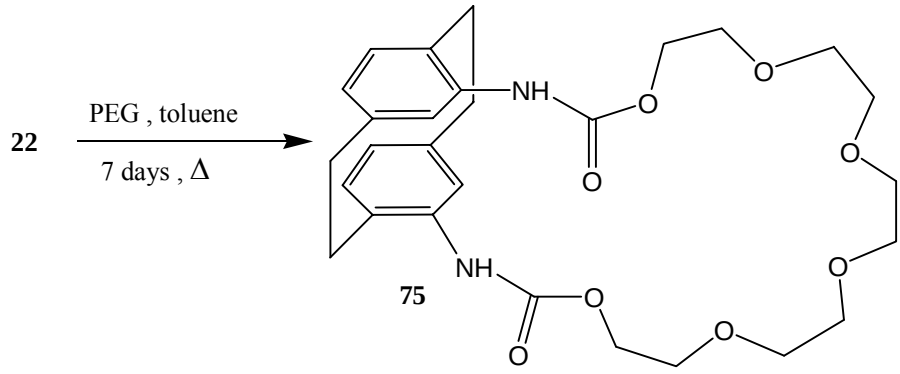
Colourless, plate-shaped crystals of X-ray quality were obtained by slow diffusion of pentane into a solution of **74** in dichloromethane. Compound **74** crystallises in the $P2_12_12_1$ (orthorhombic) unit cell. Interestingly, a look into the packing diagram reveals that the molecule has extensive inter- and intra- molecular hydrogen bonding. A very strong intramolecular hydrogen bond (2.069 Å) was observed between [N(2)-H(02)…O(1)] and four intermolecular hydrogen bond [N(1)-H(01)…O(4) (2.28 Å), C(2)-H(2A)…O(3) (2.47 Å), C(20)-H(20B)…O(7) (2.58 Å), C(23)-H(23A)…O(7) (2.66 Å)] were additionally observed. The size of the cavity, considering O(6), O(5), O(4) and O(1) is approximately 2.5 Å. Gas phase geometrical optimisation calculations using DFT theory (B3LYP/6-31G(d) programme) to determine the strength (Compliance constant) of the intramolecular hydrogen bond [N(2)-H(02)…O(1)] was found to be 6.645 Å/mdyn. The value is similar to typical strong hydrogen bonding involved in alpha helix (adenine-thymine base pair; 6.0-7.5 Å/mdyn).[67]

Thermal isomerisation of compound **74** in refluxing triglyme resulted in the decomposition of the compound yielding a dark brown intractable material. Evidently it is not possible to introduce a tetraethylene glycol bridge between two *pseudo-para* positioned amino groups.

2.2.5 *Pseudo-ortho*-crownophane (75)

Crownophane (**75**) has one OCH_2CH_2 moiety more than **74**, and hence should possess a larger cavity and in turn could be expected to exhibit different complexation and selectivity properties. The synthesis of **75** was similar to the synthesis of **74**. Treatment of 4,16-

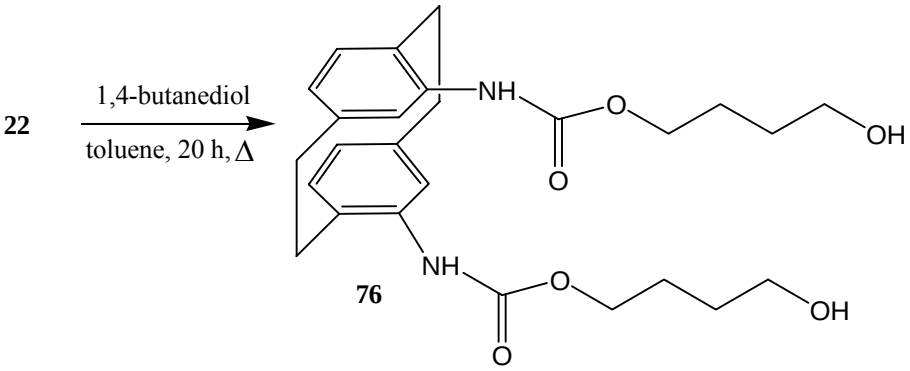
diisocyanato[2.2]paracyclophane (**22**) with pentaethylene glycol (PEG) in anhydrous toluene under high dilution conditions over a week produced the desired **75** in 73% yield. In the ^{1}H NMR spectrum, a broad singlet appears at $\delta = 7.35$ corresponding to the NH protons, and at 6.70 a broad peak for 5-H is observed which may be due to the restricted C-N bond rotation. In the mass spectrum the molecular ion peak is detected at *m/z* = 528 (41%), which undergoes fragmentation by loss of one CO_2 moiety to give *m/z* = 484 (5%).



Scheme 37. Synthesis of crownophane (**75**).

2.2.6 4,16-Dicarbamicacid(4-hydroxybutyl)ester[2.2]paracyclophane (76)

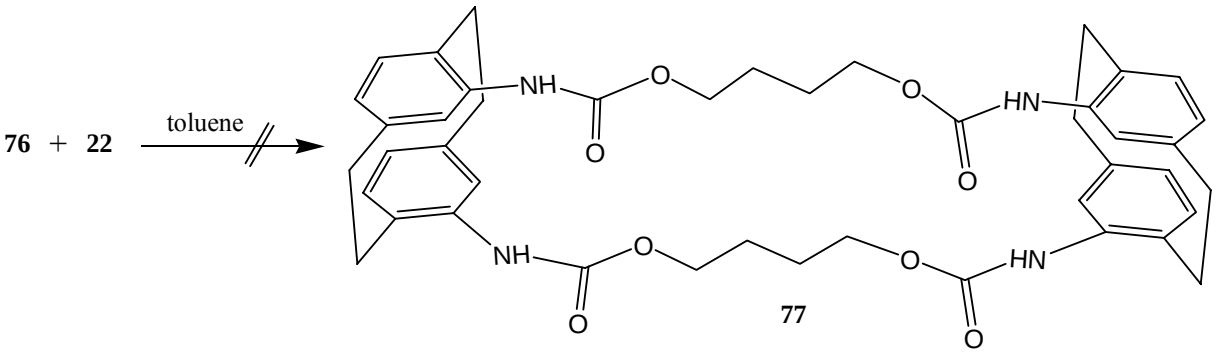
Paracyclophanes bearing long aliphatic units with a terminal polar group may prove to be good starting materials for CVD polymerisation as the polymers would then have both hydrophobic and hydrophilic ends.



Scheme 38. Synthesis of 4,16-dicarbamicacid(4-hydroxybutyl)ester[2.2]paracyclophane (**76**).

Slow addition of a solution of 4,16-diisocyanato[2.2]paracyclophane (**22**) to a refluxing solution of 1,4-butanediol in dry toluene for 20 hours produced **76** in 43% yield (Scheme 38).

Compound **76** is quite stable and can be purified by column chromatography. The compound has a very low melting point (60 °C), possibly due to the long aliphatic chains.

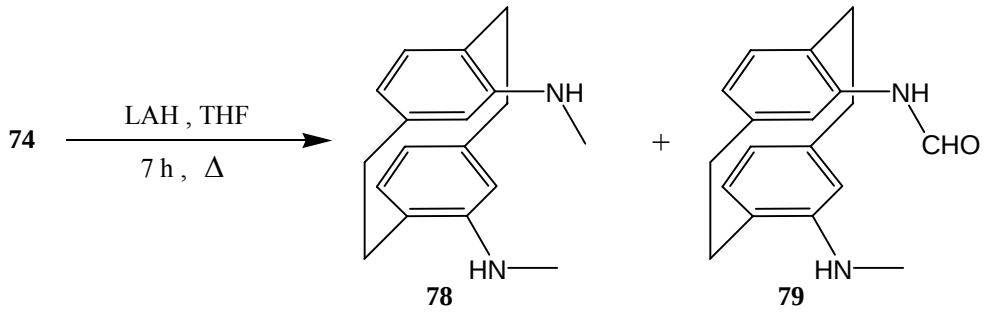


Scheme 39. Attempted synthesis of **77**.

The terminal hydroxyl groups, extend the possibility of further cyclisation with another molecule of 4,16-diisocyanato[2.2]paracyclophane (**22**) which would result in the macrocycle **77**. However, treatment of **76** with **22** under similar experimental conditions as above, yielded an intractable polymeric material. It thus appears that polymerisation is favoured over ring closure.

2.2.7 Reduction of 74 with lithium aluminium hydride

In an attempt to reduce the carbonyl moiety of the crownophane (**74**) to obtain a cyclophane with even greater resemblance to a crown ether, loss of the crown bridge was observed producing two amino derivatives. Subjection of compound **74** to reduction with a fivefold excess of LAH in refluxing tetrahydrofuran yielded *pseudo-ortho*-(*N*-methyl)(*N*′-methyl)diamino[2.2]paracyclophane (**78**) in 55% yield as a colourless solid and *pseudo-ortho*-(*N*-formyl)(*N*′-methyl)diamino[2.2]paracyclophane (**79**) in 18% yield (Scheme 40). Both compounds are highly sensitive and decompose on exposure to light and also with time. Hence exposure to light was avoided throughout the process of the reaction, workup and also during column chromatography. In the ^{13}C NMR spectrum the carbonyl carbon of **79** appears at δ = 163 (shifted upfield due to the electron rich NH group) and in the IR spectrum the corresponding band due to the carbonyl absorption is registered at 1662 and 1634 cm^{-1}.



Scheme 40. LAH reduction of **74**.

Compound **79** was recrystallised using CH_2Cl_2/pentane which yielded tablet-shaped single crystals of X-ray quality. **79** crystallise in *P2₁/n* (monoclinic) unit cell and has one intramolecular [N(1)-H(01)...O(1) (2.02 Å)] and two intermolecular [N(2)-H(02)...O(2) (2.23 Å), C(9)-H(9A)...O(2) (2.67 Å)] hydrogen bonds. Also short intermolecular C-H…π interaction [C(17)-H(17)…Cg (12, 13, 15, 16) (2.50 Å, 174 °)] was observed.

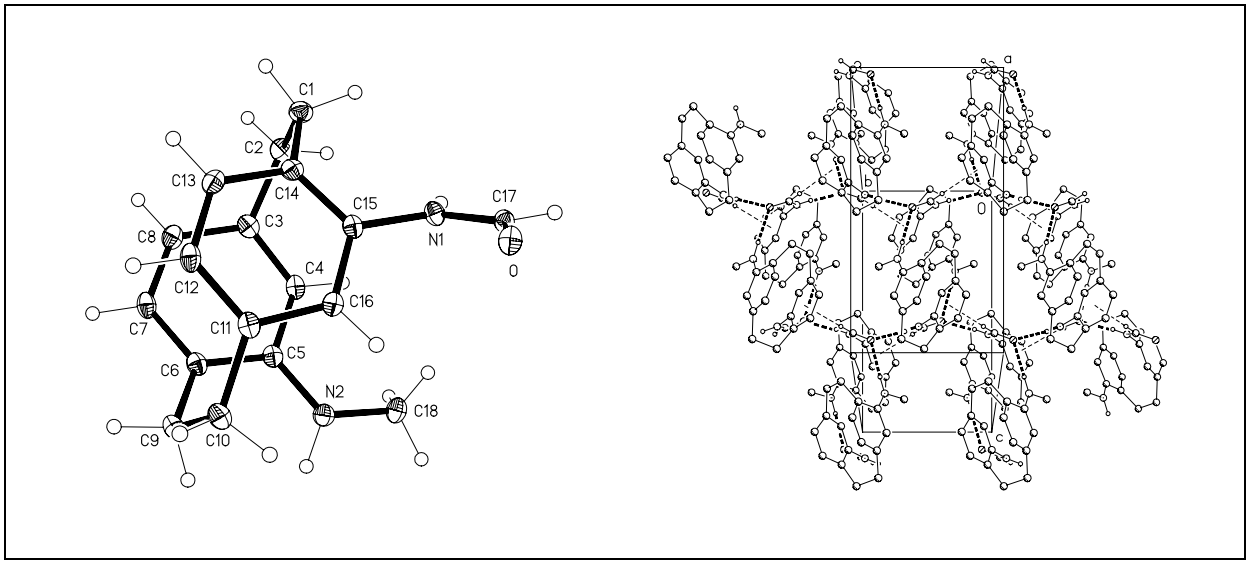
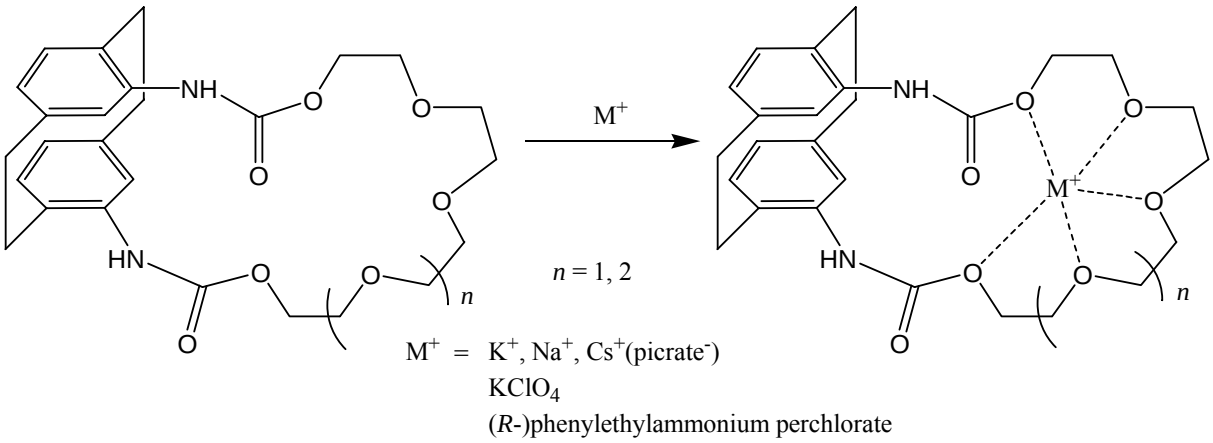


Fig. 6. Crystal structure and packing diagram of **79**.

2.2.8 Host–guest chemistry of crownophanes 74 and 75

The discovery[29] that cations and anions form stable complexes with macrocyclic polyethers and polyamines has opened the door to several fruitful areas of chemical investigation. The interest in these macrocycles rose high at the discovery of preferential complexation of certain macrocycles with alkali and alkaline earth metal ions, when the relative sizes of the cation and ligand cavity were matching.[30] Chiral derivatives of macrocycles can distinguish between enantiomers of optically active organic cations[31] and have even been used in their separation.



Scheme 41. Complexation reaction of crownophanes (**74**) and (**75**).

Alkali metal picrate salts and chiral ammonium perchlorate salts were used for the complexation reactions of crownophanes **74** and **75** (Scheme 41). The complexation reactions were carried out in NMR tubes using $CDCl_3$ as solvent and were studied by means of ^1H NMR spectroscopy and mass spectrometry. Various alkali metal picrates like Na, K and Cs and chiral (*R*-)phenylethylammonium perchlorate were used for the complexation studies. A careful analysis of the NMR spectra reveals an initial downfield shift of about 0.013 ppm and no further appreciable changes indicating very low or no complexation occurring. In electron spray ionisation mass spectrometry, the formation of crownophane-Na^+ complex was found to be more predominant, crownophane (**74**)-Na^+ complex *m/z* = 507 (100%); K^+ complex *m/z* = 523 (< 2%); Cs^+ complex *m/z* = 617 (< 2%), crownophane (**75**)-Na^+ complex *m/z* = 551 (100%); K^+ complex *m/z* = 567 (14%); Cs^+ complex *m/z* = 661 (2%), indicating selectivity and stability towards the Na^+ ion. Unfortunately, no crystals of the salts could be obtained to allow X-ray crystal structure analysis.

DFT calculations (B3LYP/6-31G(d) programme) reveal that the complexation energy of crownophane (**74**) with K^+ ion is -58.1 kcal/mol whereas with Na^+ is -84.2 kcal/mol, which means sodium ion complexes more strongly by ca. 26 kcal/mol than the potassium ion. This is in accordance with the ESI mass spectrometry result, where the formation of crownophane-Na^+ complex was found to be predominant. Though the calculations and the mass spectrometry results are in agreement, both involving gas phase, it should not be forgotten that from the NMR experiments no significant complexation behaviour could be observed which could be attributed to solvent effects.

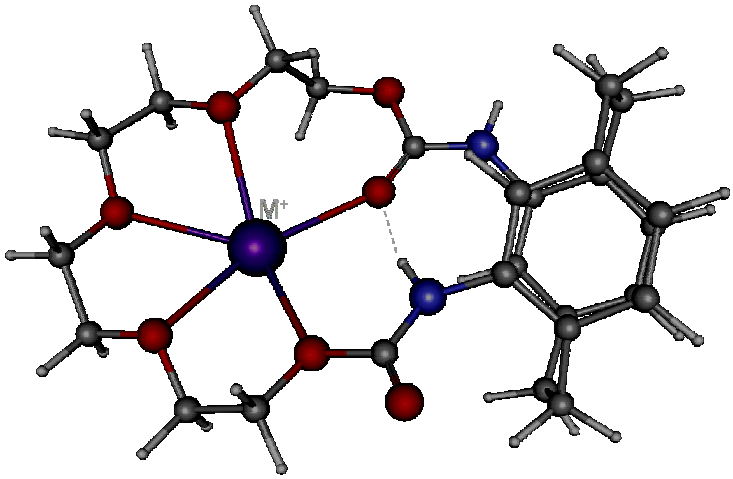
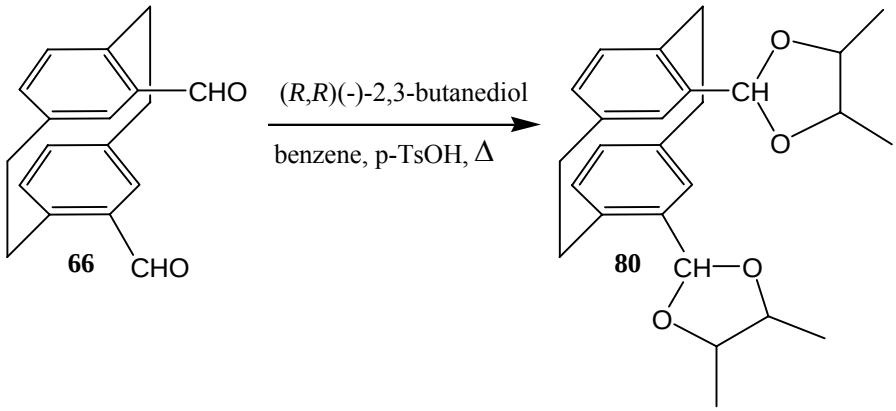


Fig. 7. B3LYP/6-31G(d) gas phase optimisation of crownophane (**74**) with Na^+ ion.

2.2.9 Resolution of chiral *pseudo-ortho* substituted [2.2]paracyclophanes

Compared to many classical optically active reagents, substituted [2.2]paracyclophanes offer the advantage of not only possessing no racemizable α-hydrogen atom but also show a very high configurational stability. Resolution of the chiral crownophanes **74**, **75** and 4,16-diisocyanato[2.2]paracyclophane (**22**) are of importance from the point of their applications in chiral syntheses. The resolution can be performed either on the final molecules or one of the precursors. Separation of enantiomers by means of chiral column chromatography is often difficult, whereas many chiral diastereomers have been separated by standard methods even in gram quantities. Hence it was suggested that the resolution could be performed by converting the enantiomeric *pseudo-ortho*-diformyl[2.2]paracyclophane (**66**) to the corresponding chiral acetal diastereomers.



Scheme 42. Synthesis of bisacetal **80**.

4,16-Diformyl[2.2]paracyclophane (**66**) was hence treated with commercial (*R*,*R*)(−)-2,3-butanediol in refluxing benzene and catalytic amount of *p*-TsOH to give the corresponding bisacetal **80** quantitatively, the spectral data are in accordance with the ref.[53] Attempts to separate the diastereomeric mixtures of the acetal by column chromatography or preparative thin layer chromatography or by semi preparative HPLC failed though.

Recently optical resolution of 4,7-dicarboxy[2.2]paracyclophane was achieved using (*S*)-phenylethylamine through formation of the corresponding diastereomeric salt.[54] Hence the *pseudo-ortho*-dicarboxy[2.2]paracyclophane (**67**) could prove to be a good candidate for optical resolution. Chiral amines like (*R*)-phenylethylamine and naturally occurring chiral compounds like *l*-menthol, cinchonidine were treated with **67** in dry solvents like acetonitrile, chloroform under reflux and various concentrations. The resulting compounds were hydrolysed in 2N aq. HCl. The dicarboxy[2.2]paracyclophane hence obtained was analysed by reverse phase chiral HPLC and optical rotation measurements revealed no resolution.

The crownophanes **74**, **75** and *pseudo-ortho* diisocyanato[2.2]paracyclophane (**22**) were successfully separated by chiral analytical HPLC using cellulose tris(3,5-dimethylphenylcarbamate) (CDMPC) and amylase tris(3,5-dimethylphenylcarbamate) (ADMPC) as chiral stationary phases.[22] Compounds **22**, **74** and **75** were completely resolved giving elution times (see table below) t_1 and t_2 for (+) and (-) isomers, respectively. In all the three cases the (+)-isomer was eluted first. Capacity factors, k_1 [= $(t_1 - t_0)/t_0$)] and k_2 [= $(t_2 - t_0)/t_0$)], represent the strength of the interaction between the stationary phase and the enantiomers, respectively. The crownophanes **74** and **75** exhibit better interaction (k_1 = 19.7 and 22.0, k_2 = 42.9 and 42.0, respectively) with the stationary phase compared to the isocyanate derivative **22** (k_1 = 2.00, k_2 = 10.73). The chiral recognition ability of the chiral stationary phase can be evaluated from the separation factor α (= k_2/k_1), and the resolution of two peaks is expressed by the resolution factor R_s [= $2(t_2 - t_1)/(W_1 + W_2)$]. *Pseudo-ortho*-diisocyanato[2.2]paracyclophane (**22**) has α = 5.37 and the best resolution factor R_s = 11.54. It is also noteworthy to mention that in most separations CDMPC showed higher optical resolving ability than ADMPC. The results of the optical resolution of **22**, **74** and **75** are summarized in Table 4.

Compound	µL injected	t_1 (min)	t_2 (min)	First eluted enantiomer	k_1	k_2	α	R_s
22	20	4.5	17.6	+	2.0	10.7	5.37	11.54
74	20	31.0	65.8	+	19.7	42.9	2.18	6.51
75	20	34.5	64.5	+	22.0	42.0	1.91	4.99

CDMPC-column, eluent: *n*-hexane/propan-2-ol, flow rate: 2 mL/min, back pressure: 42 bar, t_0 [tri(*t*-butyl)-benzene]: 1.5 min, sample dissolved in *n*-hexane/propan-2-ol/$CHCl_3$ (63/7/30).

Table 4. Optical resolution of [2.2]paracyclophane derivatives **22**, **74** and **75** on CDMPC.

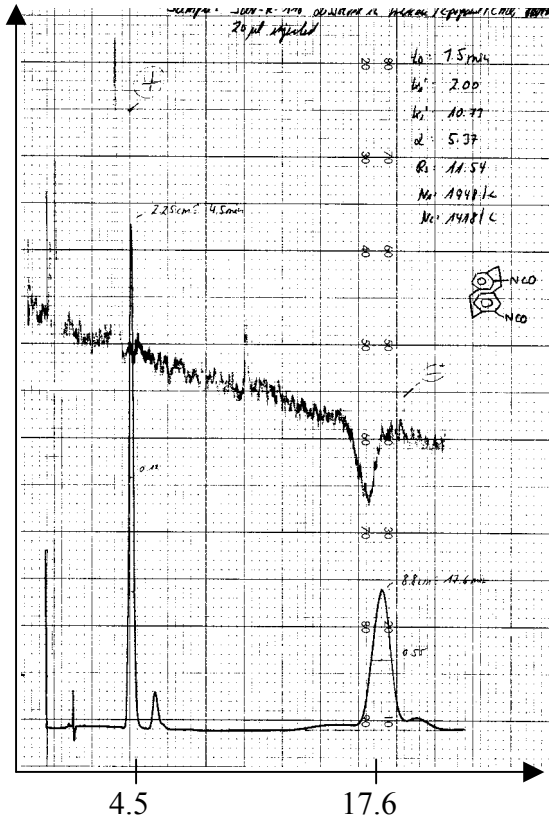


Fig. 8. Optical resolution of 4,16-diisocyanato[2.2]paracyclophane (**22**) on CDMPC.

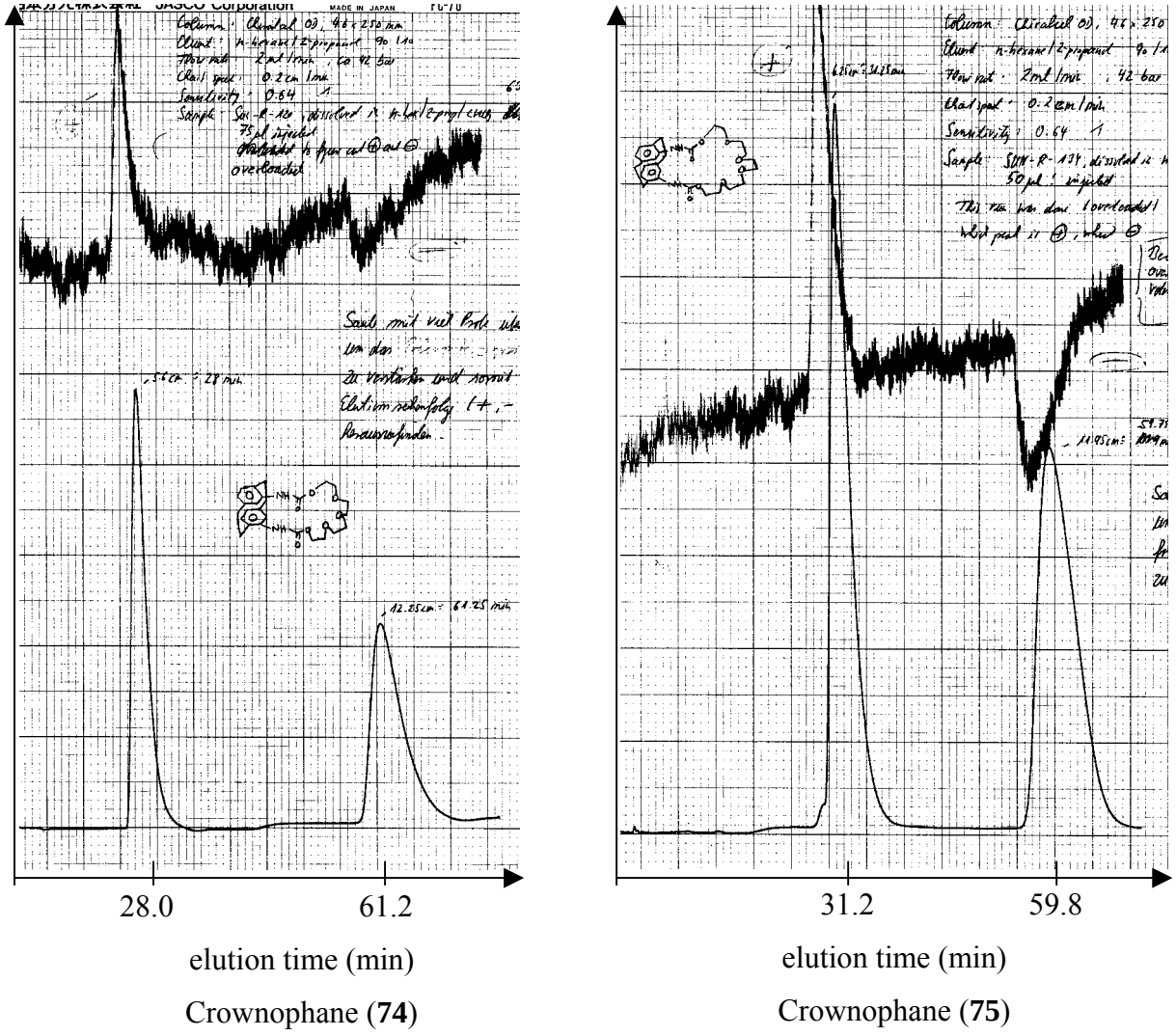


Fig. 9. Optical resolution of crownophanes **74** and **75** on CDMPC.

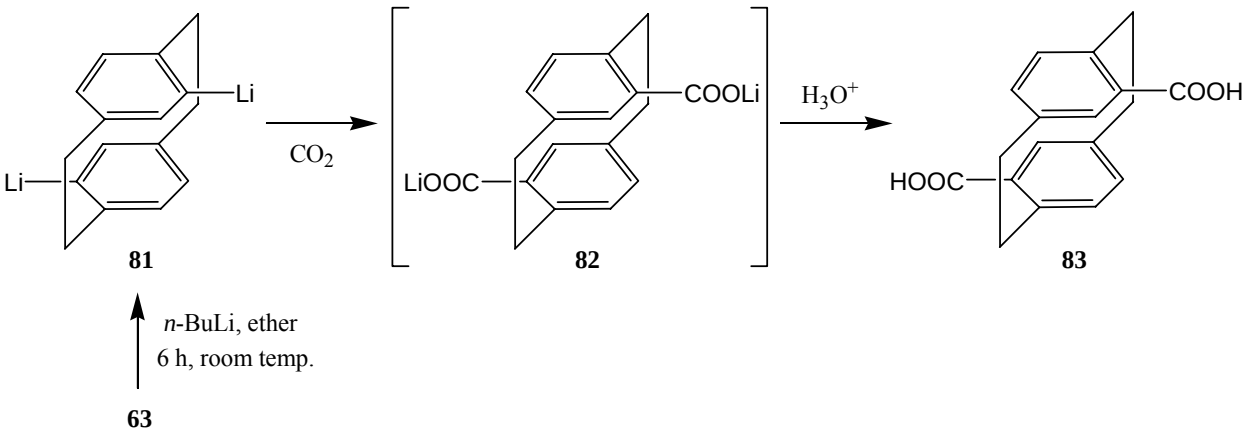
Having established the possibility of analytical separation, it should be possible to find conditions also for separations on a preparative scale.

2.3 Synthesis and reactions of *pseudo-para*-diisocyanato[2.2]paracyclophane (23)

2.3.1 4,12-Dicarboxy[2.2]paracyclophane (83)

The synthesis of **83** was achieved as early as 1969 by Yeh and Gorham,[32] from 4,12-dibromo[2.2]paracyclophane (**63**) by dilithiation using *n*-BuLi in refluxing benzene, in the presence of Cu powder as a catalyst, and further treatment of the produced **81** with excess of solid carbondioxide (Scheme 43). The procedure adopted for the synthesis of *pseudo-para*-dicarboxy acid **83** was similar to that of the synthesis of the *pseudo-ortho*-dicarboxy[2.2]paracyclophane (**67**) by Rozenberg *et al.*[24] which involves much milder

reaction conditions (room temperature). As a matter of fact the ratio of dibromophane **63** to that of *n*-BuLi used for lithiation was 1:2, which is much less compared to the reported procedure.[24]

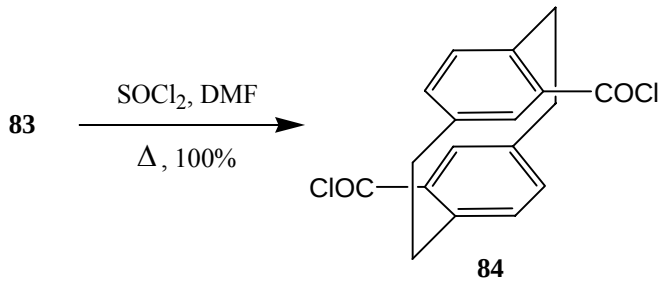


Scheme 43. Synthesis of *pseudo-para*-dicarboxy[2.2]paracyclophane (**83**).

Slow addition of *n*-BuLi to a clear solution of **63** in dry diethylether at room temperature with stirring, results in the formation of **81** which on further treatment with excess of dry ice leads to the insertion of the CO_2 moiety. On acidic work up with conc. HCl the desired 4,12-dicarboxy[2.2]paracyclophane (**83**) is obtained in 40% yield as colourless amorphous substance. The diacid is highly insoluble in most of the organic solvents and was used as such for further reactions.

2.3.2 4,12-Bis(azidocarbonyl)[2.2]paracyclophane (85)

Treatment of 4,12-dicarboxy[2.2]paracyclophane (**83**) with freshly distilled thionyl chloride in the presence of a catalytic amount of DMF under reflux produced 4,12-bis(chlorocarbonyl)-[2.2]paracyclophane (**84**) quantitatively. Normally, acid chlorides are highly reactive and are used immediately for further reactions. Amazingly **84** was found to be a stable compound and having a very high melting point (210 °C) which may be attributed to the compound's symmetry and crystal packing.



Scheme 44. Synthesis of 4,12-bis(chlorocarbonyl)[2.2]paracyclophane (**84**).

The protons 5-H and 13-H appear at δ = 7.40 in the ^{1}H NMR spectrum due to the strong electron withdrawing effect of the chlorocarbonyl moiety. In the IR spectrum, very strong bands due to the carbonyl stretching mode are registered at 1765 and 1677 cm^{-1}. Also interestingly, though not a highly conjugated system, **84** exhibit an absorption maximum at 316 nm in the UV/Vis. spectrum.

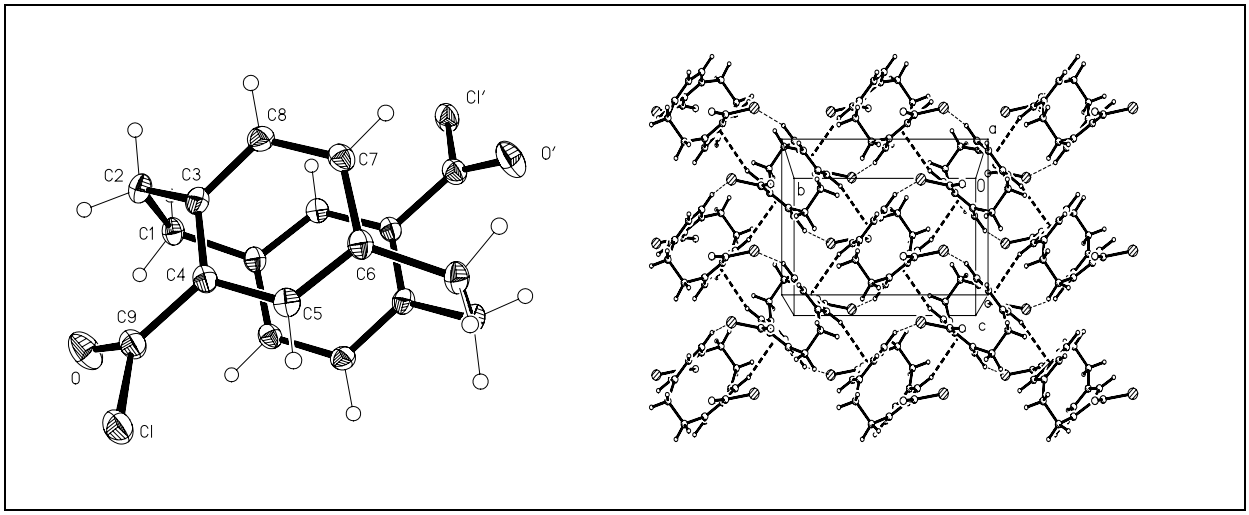
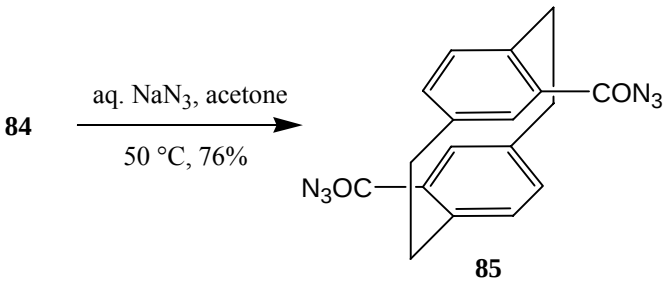


Fig. 10. Crystal structure and packing diagram of **84**.

Tablet-like single crystals of X-ray quality were obtained by the diffusion method using dichloromethane/pentane. Compound **84** crystallises in *P2$_1$/n* (monoclinic) unit cell and was found to have two strong intermolecular hydrogen bonds [C(8)-H(8)...Cl (3.01 Å), C(7)-H(7)...O (2.57 Å)].

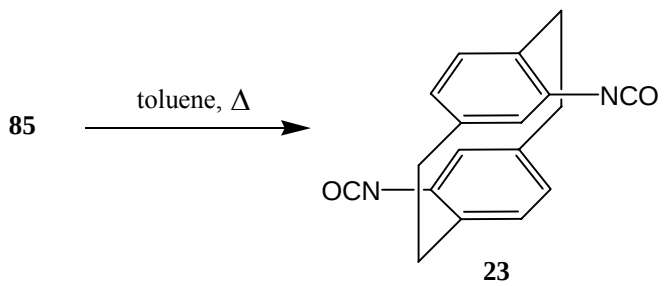


Scheme 45. Synthesis of 4,12-bis(azidocarbonyl)[2.2]paracyclophane (**85**).

Subjection of **84** to nucleophilic substitution with aq. sodium azide yields 4,12-bis(azidocarbonyl)[2.2]paracyclophane (**85**) in 76% as a colourless amorphous solid (Scheme 45). A difference in this reaction compared to the preparation of the corresponding *pseudo-ortho*, **69**, or *pseudo-geminal*-derivatives, **47**, is that the reaction is carried out at 50 °C. This reactivity difference actually helps to obtain the *pseudo-ortho*-isomer **69** in pure form (as a slight contamination of the *pseudo-para*-isomer is always present), as the reaction in the former case is carried out under ice cold conditions. In comparison to **84** compound **85** has a relatively low melting point (110 °C). In the IR spectrum two strong bands due to the azido and carbonyl groups are registered at 2137 and 1679 cm^{-1}, respectively.

2.3.3 4,12-Diisocyanato[2.2]paracyclophane (23)

Subjection of compound **85** to Curtius rearrangement, by refluxing it in dry toluene, produces 4,12-diisocyanato[2.2]paracyclophane (**23**) by the elimination of nitrogen, in 30% yield as a colourless crystalline solid. In the ^1H NMR spectrum, 5-H and 13-H are highly shielded due to the electron donating isocyanate functionality and appear at $\delta = 5.89$ as a doublet with a *meta* coupling constant of 1.74 Hz. In the IR spectrum, very strong bands due to the isocyanate group appear in the cumulative double bond region at 2272 and 2253 cm^{-1}. In the mass spectrum, the molecular ion peak appears at *m/z* = 290 which undergoes symmetrical cleavage into two halves giving rise to the base peak *m/z* = 145 (C_9H_7NO).



Scheme 46. Synthesis of 4,12-diisocyanato[2.2]paracyclophane (**23**).

Plate-shaped single crystals of X-ray quality were obtained by slow diffusion of pentane into a saturated solution of **23** in dichloromethane. Compound **23** crystallises in $P2_12_12_1$, orthorhombic unit cell and the packing pattern is "7,11", which is similar to that of the *pseudo-geminal*-dihalo derivatives **20** and **21**. Three strong inter molecular hydrogen bonds were observed [C(1)-H(1B)...O(1) (2.60 Å), C(7)-H(7)...O(1) (2.62 Å), C(15)-H(15)...O(2) (2.65 Å)] and also there are strikingly short intermolecular contacts from hydrogen atoms to the centroid of the rings [C(16)-H(16)…Cg(3, 4, 5, 6, 7, 8) (2.80 Å, 161°), C(8)-H(8)...Cg(11, 12, 13, 14, 15, 16) (2.86 Å, 158°)].

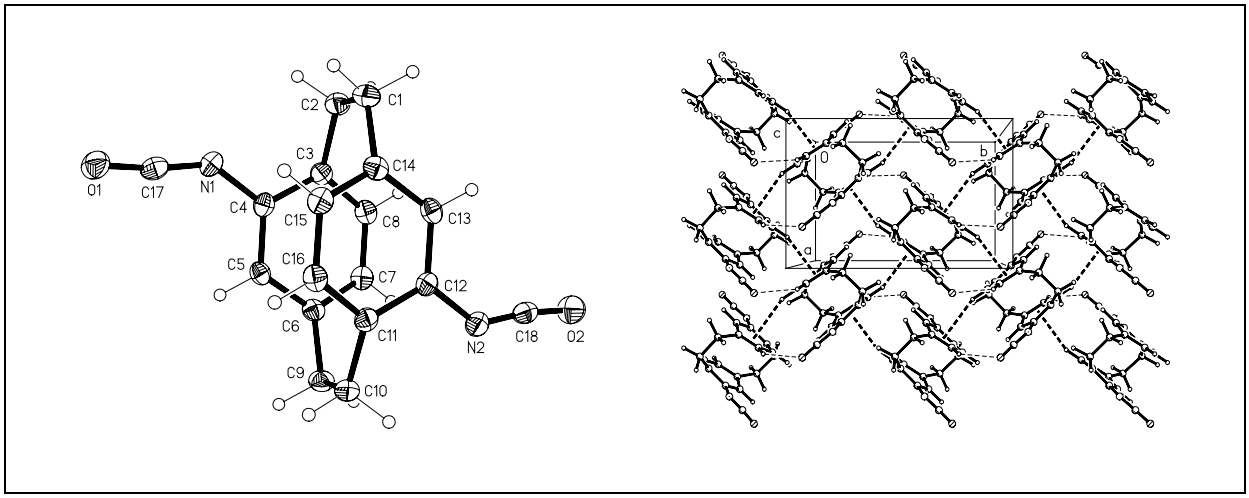
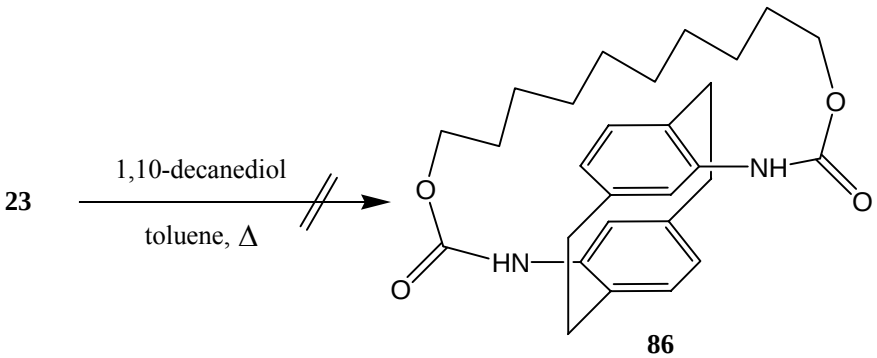


Fig. 11. Crystal structure and packing diagram of **23**.

In an attempt to introduce a further bridge in **23**, 1,10-decanediol was added slowly at the rate of 3 ml/h to a refluxing solution of the diisocyanate **23** in dry toluene under nitrogen atmosphere. The reaction mixture was refluxed with stirring over a week and on working up yielded only intractable material.

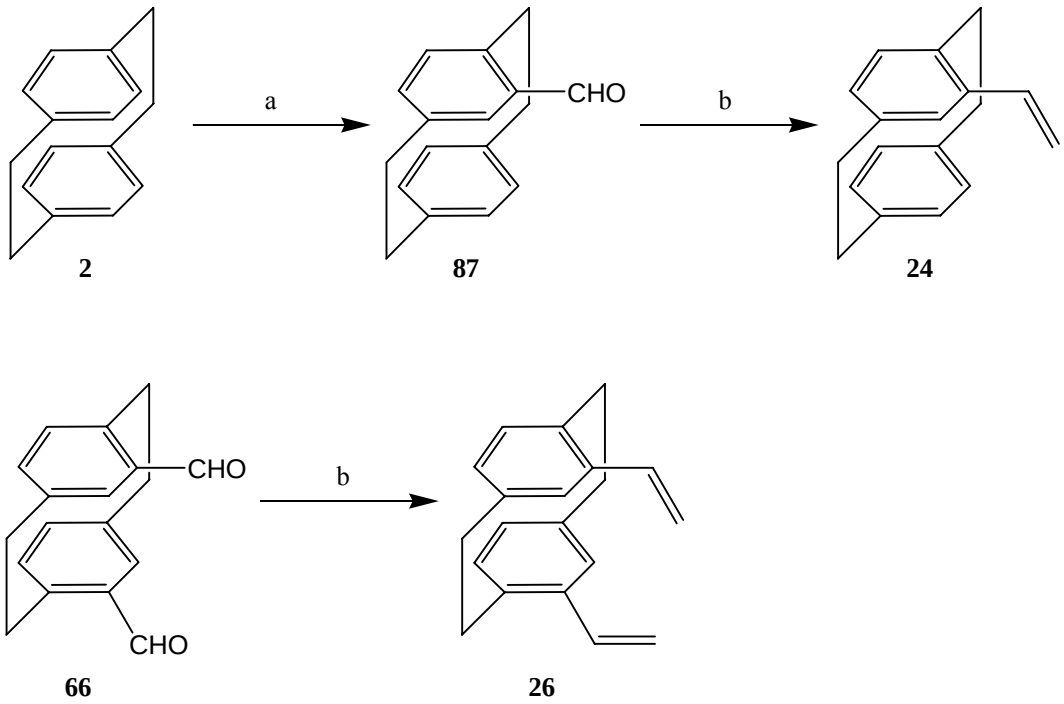


Scheme 47. Attempted synthesis of compound **86**.

It would be very interesting to study the through space interaction between the aromatic ring and the hydrogen atoms of the bridge in compound like **86** by ^{1}H NMR spectroscopy and also the conformational orientation of the hydrogen atoms (rotational barrier).

2.4 Syntheses of chiral hydroborating reagents

As already mentioned in Chapter 1.4.3, the ethenyl[2.2]paracyclophanes **24** and **26** being planar chiral in nature could prove to be good starting materials for the preparation of chiral hydroborating agents.



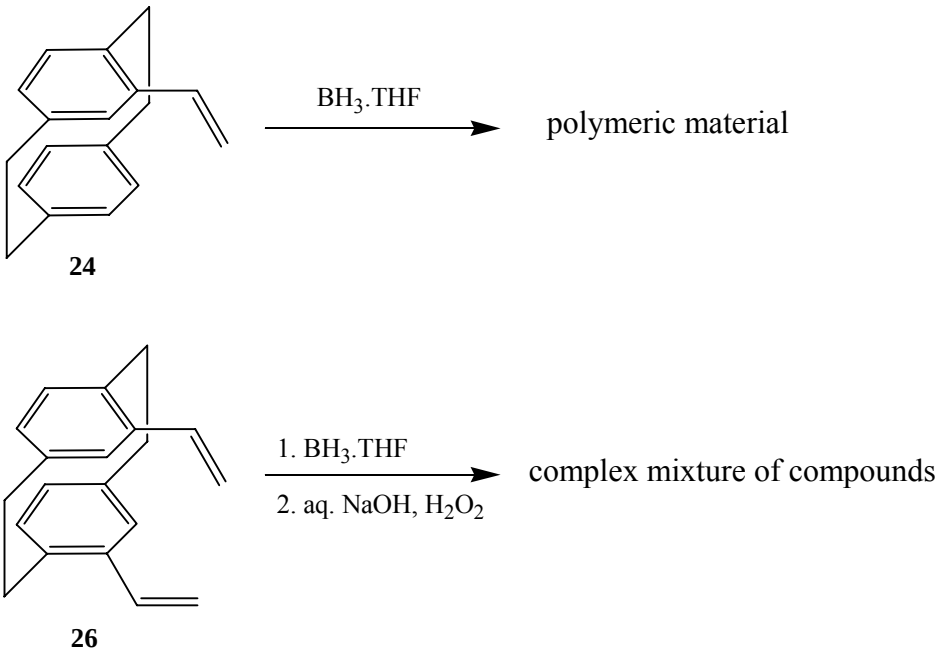
a) $TiCl_4$, CH_3OCHCl_2, CH_2Cl_2; b) CH_3PPh_3Br, *n*-BuLi, THF.

Scheme 48. Synthesis of ethenyl[2.2]paracyclophanes **24** and **26**, respectively.

4-Ethenyl[2.2]paracyclophane (**24**) could be easily synthesised in good yields from the corresponding aldehyde 4-formyl[2.2]paracyclophane (**87**) by Wittig reaction (Scheme 48).[33] Compound **87** in turn is obtained from [2.2]paracyclophane (**2**) by Rieche formylation, also in appreciable yields. The synthesis of 4,16-diethenyl[2.2]paracyclophane (**26**) was also accomplished from the corresponding diformyl derivative **66**, by a Wittig reaction.[33] The synthesis of compound **66** has been already discussed in the Section 2.2.1.

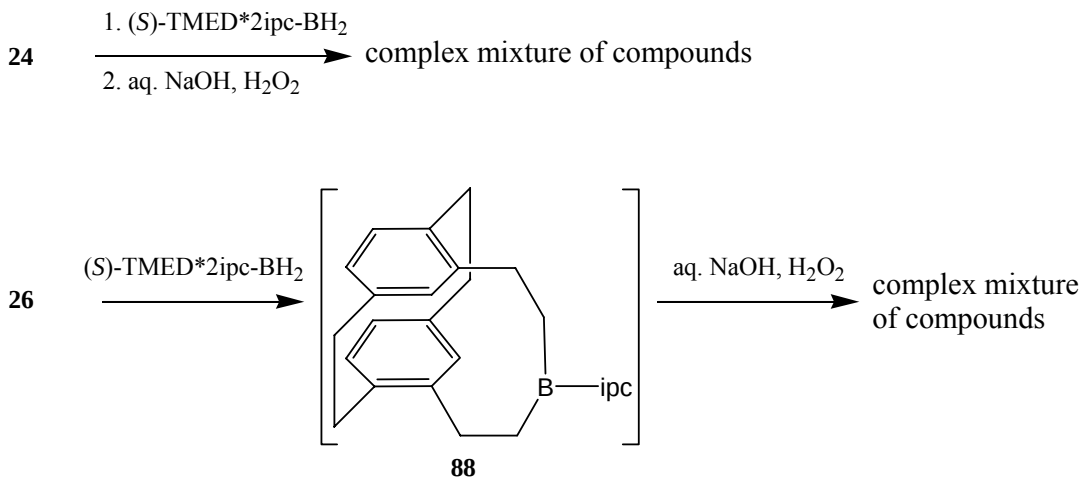
Treatment of **24** with the BH_3.THF complex resulted in the formation of an insoluble product precipitating out of the reaction. The reaction procedure adopted was similar to the

preparation of 9-BBN[34] by Brown *et al.* Spectroscopic analysis of the product revealed the formation of polymeric material. The diethenyl derivative **26** was subjected to the same reaction conditions as above and the adduct obtained was further oxidised using 35% H_2O_2 and aq. NaOH, expecting to yield the corresponding diol.[35] Though an initial colourless precipitate was formed as expected from the reaction of **26** with BH_3.THF complex, the subsequent oxidation resulted in a complex mixture of compounds/polymeric material, analysed by ^{1}H NMR spectroscopy (Scheme 49).



Scheme 49. Hydroboration of ethenyl[2.2]paracyclophanes **24** and **26** using BH_3.THF complex.

An alternative approach would be to use chiral boranes for the hydroboration reaction; this would also be helpful in the resolution of the racemic ethenyl paracyclophanes. (*S*)-Alpine boramine (isopinocampheyl boramine) complex, a stable naturally occurring chiral reagent was employed for the hydroboration of **24** and **26**. Again the initial adducts were further oxidised using aq. NaOH and hydrogen peroxide solution. The resulting colourless material was analysed by ^{1}H NMR spectroscopy, revealing a complex mixture of polymeric materials. The failure of the hydroboration and oxidation maybe due to the ethenyl moiety being prone to oligomerisation and polymerisation under Lewis acid conditions.



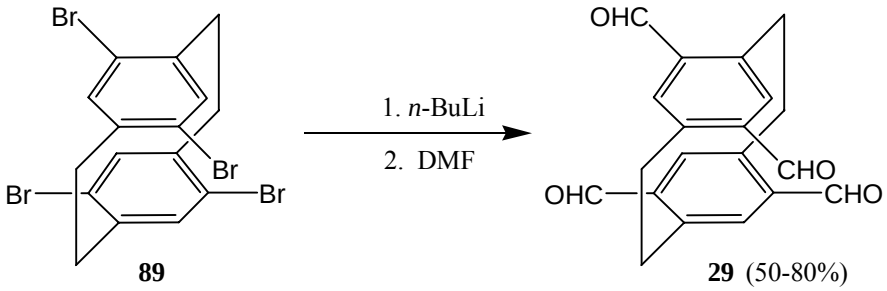
Scheme 50. Attempted synthesis of hydroboration and resolution of **24** and **26**.

2.5 Synthesis and reactions of multifunctionalised [2.2]paracyclophanes

Multifunctionalised cyclophanes are of importance as they offer additional possibilities for modifications and derivatisation. Highly functionalised [2.2]paracyclophanes are also interesting substrates for CVD polymerisation. The importance of the tetraformyl and tetraacetyl [2.2]paracyclophane has already been mentioned in Chapter 1.4.4.

2.5.1 4,7,12,15-Tetraformyl[2.2]paracyclophane (29)

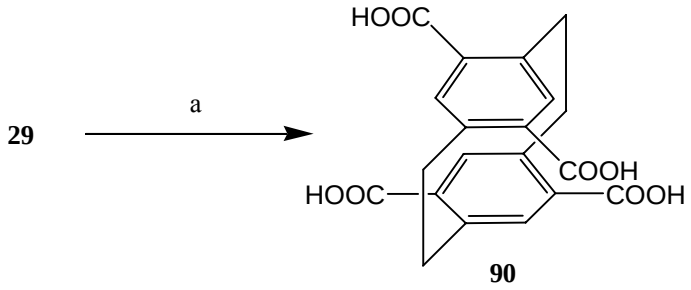
As already mentioned, compound **29** has been mentioned in the literature[19] but neither the complete synthesis nor the spectroscopic data are available. The shortest and the easiest route to realise **29** would be from 4,7,12,15-tetrabromo[2.2]paracyclophane (**89**) by simple lithiation followed by formylation (Scheme 51). Compound **89** was subjected to lithiation using a large excess of *n*-BuLi (eighty equivalents of *n*-BuLi for one equivalent of compound **89**) at room temperature with stirring over a period of 6 hours. To this tetralithiated paracyclophane, dry DMF (<50 ppm of water) was added slowly at room temperature and the reaction continued overnight. On working up and by means of simple precipitation using dichloromethane/pentane mixture, compound **29** was obtained as a pale yellow solid.



89 **29** (50-80%)

Scheme 51. Synthesis of 4,7,12,15-tetraformyl[2.2]paracyclophane (**24**).

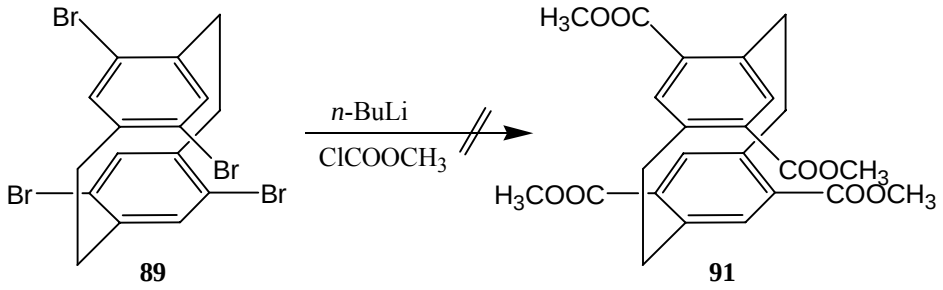
A disadvantage of this reaction is the usage of a large excess of *n*-BuLi; furthermore the reaction could only be performed in smaller quantities (100 mg). Also the yield of this reaction was not constant and ranged between 50 and 80%. Compound **29** decomposes above 260 °C. In the ^{1}H NMR spectrum, sharp singlets corresponding to the formyl and the aromatic protons appear at δ = 9.95 and 6.99, respectively. In the IR spectrum, a very strong absorption band due to the carbonyl moiety was observed at 1683 cm^{-1}. In the mass spectrum, the molecular ion peak appears at *m/z* = 320 (64%) and the base peak at *m/z* = 132 (C_9H_8O).



a) aq. $NaH_2PO_4.H_2O$, aq. $NaClO_2$, *t*-BuOH, 2-methyl-2-butene, H_2O, room temperature.

Scheme 52. Synthesis of 4,7,12,15-tetracarboxy[2.2]paracyclophane (**90**).

The tetraformyl phane **29** was therefore subjected to further oxidation reaction using aq. sodium chlorite to produce the corresponding 4,7,12,15-tetracarboxy[2.2]paracyclophane (**90**) (Scheme 52). Compound **90** is highly insoluble in organic solvents and well soluble in water. The ^{1}H NMR spectrum (in D_2O) reveals the formation of **90**, as the aromatic protons appear as a singlet at δ = 7.05, the bridge protons appears as two symmetrical multiplets at δ = 3.69 and 2.89 and the carboxylic acid protons come along with the solvent peak. No further characterisations were possible as the compound could not be obtained in pure form due to the contamination from the inorganic reactants which are also water soluble. Due to the limitations in the synthesis of compound **29** and **90** no further derivatisations and reactions could be carried out with the tetraacid.

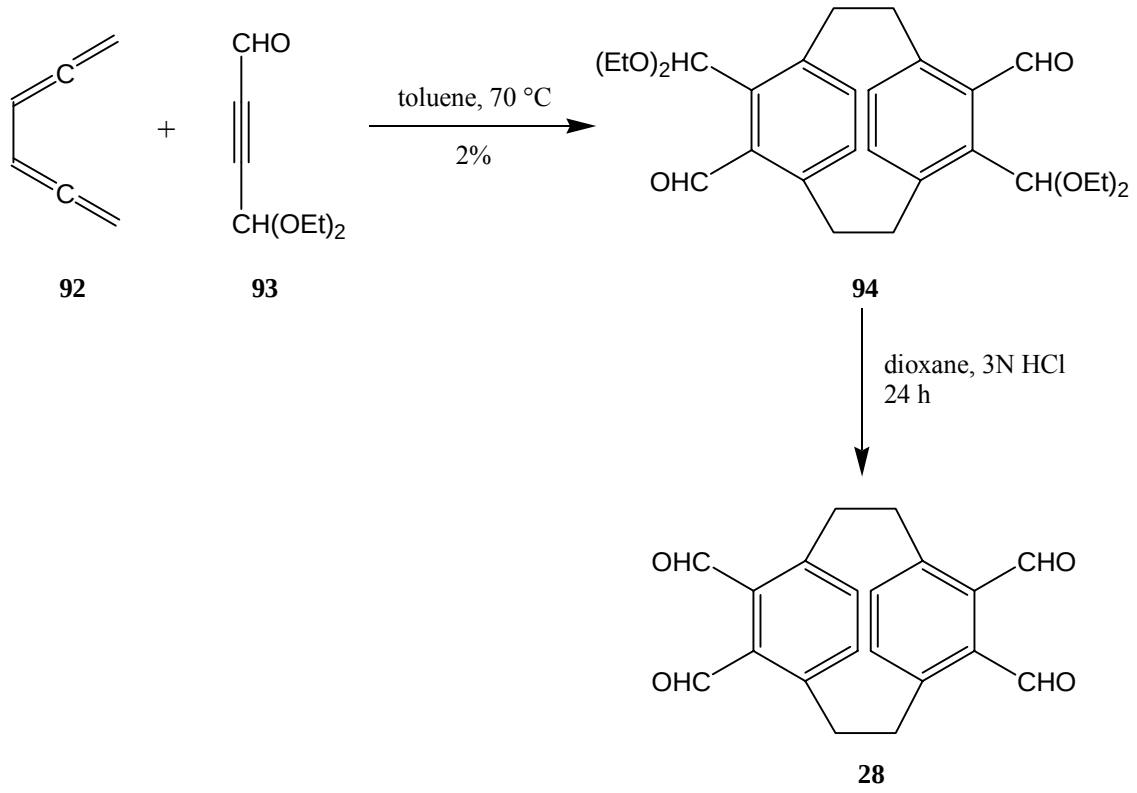


Scheme 53. Attempted synthesis of 4,7,12,15-tetramethoxycarbonyl[2.2]paracyclophane (**91**).

As the tetrabromo phane **89** could be tetralithiated, it was envisaged that by using the methyl ester derivative of chloroformic acid ($ClCOOCH_3$) it should be possible to obtain the corresponding *crossed* tetramethyl ester derivative **91**. Hence compound **89** was subjected to tetralithiation using excess *n*-BuLi under the same reaction conditions as applied in the synthesis of **29**. The metal organic intermediate was further treated with $ClCOOCH_3$ and the mixture was stirred overnight at room temperature. However, only an intractable material was obtained.

2.5.2 4,5,12,13-Tetraformyl[2.2]paracyclophane (28)

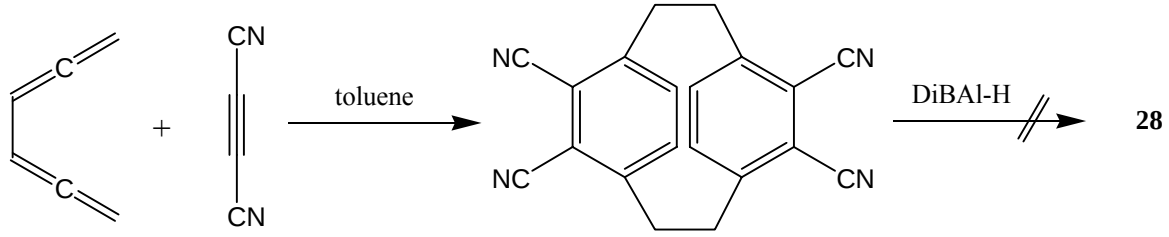
The synthesis of 4,5,12,13-tetraformyl[2.2]paracyclophane[18] (**28**) has already been accomplished but the results were irreproducible. Hence several attempts were carried out and routes were devised to arrive at a reproducible route to **28**. The reported synthesis involves the cycloaddition reaction of 1,2,4,5-hexatetraene (**92**, bisallene) with 4,4-diethoxy-2-butynal (**93**), being carried out according to the classical reactions[36] of Hopf and co-workers. Further hydrolysis of the produced bisacetals **94** using a dioxane/aq. HCl mixture, then furnished the desired tetraformyl derivative **28** (Scheme 54). Though the reaction did proceed, the main problem was associated with the yield. The reported yield amounted to 60%, but here only 2% could be realised. Various modifications of solvent and temperature had no success, toluene, benzene, 5 M lithium perchlorate in diethylether (LPDE) being tried. The reaction temperature was varied from 40 to 120 °C. As cycloaddition reactions are often catalysed by Lewis acids, the reaction was also carried out in the presence of the BF_3.etherate complex. None of these variations helped to increase the yield of **94** significantly. The above cycloaddition reaction was also performed using 4,4-dimethoxy-2-butynal[55] as the dienophile instead of the diethoxy derivative **93**, but no characteristic product could be obtained.



92 **93** **94** **28**

Scheme 54. Reported synthesis of 4,5,12,13-tetraformyl[2.2]paracyclophane (**28**).[18]

An alternative way to obtain compound **28** is by means of functional group transformation from compounds bearing the desired substitution pattern already. One such direct conversion could be the reduction of the known 4,5,12,13-tetracyano[2.2]paracyclophane (**96**)[37]. There are several procedures in the literature for conversion of the cyano to the aldehyde function,[38] and one example is the direct conversion of a dicyano cyclooctatetraenyl cyclophane[39] to the corresponding aldehyde derivative.



92 **95** **96**

Scheme 55. Attempted synthesis of **28** via the tetranitrile (**96**).

Cycloaddition reaction of bisallene (**92**) with dicyanoacetylene (**95**)[65] produced **96** in 50% yield as a pale brown, highly insoluble solid (Scheme 55). Compound **96** was subjected to diisobutylaluminium hydride (DiBAl-H) treatment at -78 °C, but on work up neither the

starting material nor the desired tetraformyl phane **28** could be obtained. The reaction was carried out at different temperatures [-78 °C, 0 °C, room temperature] but still the desired compound was not realisable. Though compound **96** has been reported, its crystallographic data are not available. Fortunately tablet-shaped crystals of X-ray quality were obtained by means of slow extraction of **96** in refluxing acetonitrile and allowing the mixture to cool to room temperature slowly. **96** crystallises in the $P2_1/n$, monoclinic unit cell. Interestingly four inter molecular hydrogen bonds exist; one from the aromatic hydrogen to a nitrogen atom of the neighbouring molecule [C(8)-H(8)...N(1) (2.69 Å)] and three from the bridge protons to the neighbouring nitrogen atoms [C(1)-H(1B)...N(2) (2.50 Å), C(2)-H(2B)...N(2) (2.55 Å), C(10)-H(10A)...N(4) (2.60 Å)]. The 3-D packing is very complex with borderline C-H…N contacts.

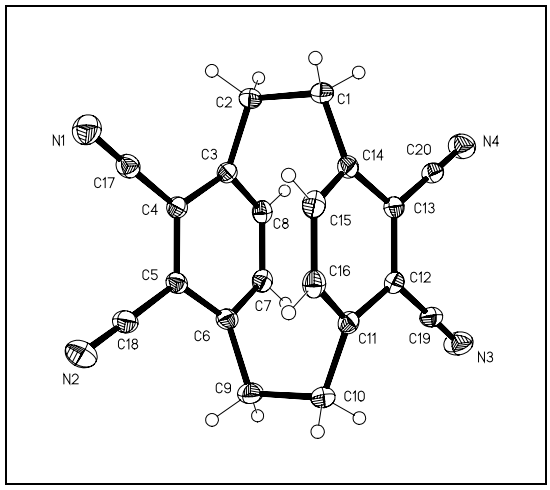
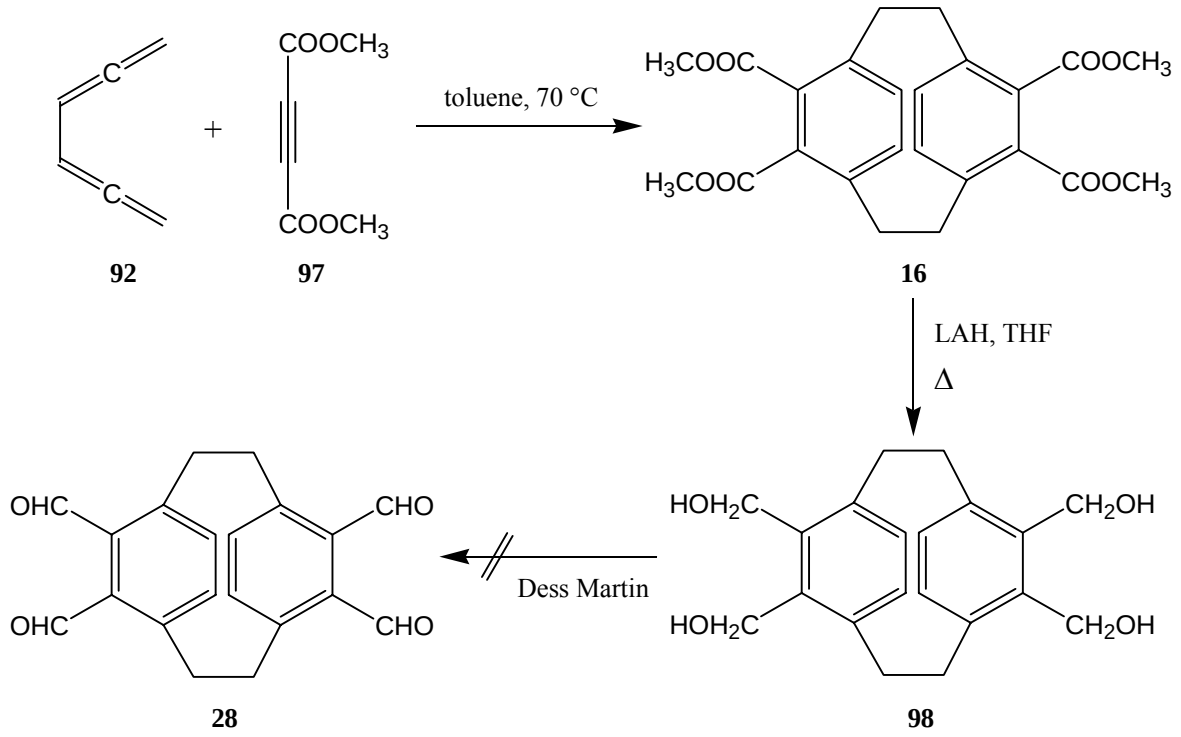


Fig. 12. Structure of 4,5,12,13-tetracyano[2.2]paracyclophane (**96**) in the crystal.

Oxidation of 4,5,12,13-tetrakis(hydroxymethyl)[2.2]paracyclophane (**98**)[37] would be an alternative way to realise **28**. Compound **98** itself could be prepared by the reduction of 4,5,12,13-tetrakis(methoxycarbonyl)[2.2]paracyclophane (**16**)[36] using lithium aluminium hydride (LAH) in refluxing THF in 75% yield. The required substrate **16** was in turn synthesised by cycloaddition of bisallene (**92**) to dimethylacetylenedicarboxylate (**97**) in 60% yield as a colourless crystalline solid. Oxidation of **98** with the Dess Martin reagent in dichloromethane resulted in a complex mixture of compounds, from which **28** could not be isolated.



Scheme 56. Oxidation reaction of **95** using the Dess Martin reagent.

Fortunately tablet-shaped crystals of X-ray quality of compound **98** were obtained, when the compound crystallised in the NMR tube. As can be seen from the crystal structure one molecule of **98** is complexed with two molecules of DMSO. The compound crystallises in the *P(-1)*, triclinic unit cell and has five hydrogen bonds (all within the same asymmetric unit) of which one is very strong showing a bond length of 1.89 Å [O(1)-H(01)...O(2) (2.063 Å), O(2)-H(02)...O(3) (1.89 Å), C(12)-H(12B)...O(2) (2.59 Å), C(10)-H(10B)...O(3) (2.61 Å), C(11)-H(11C)...O(3) (2.61 Å)].

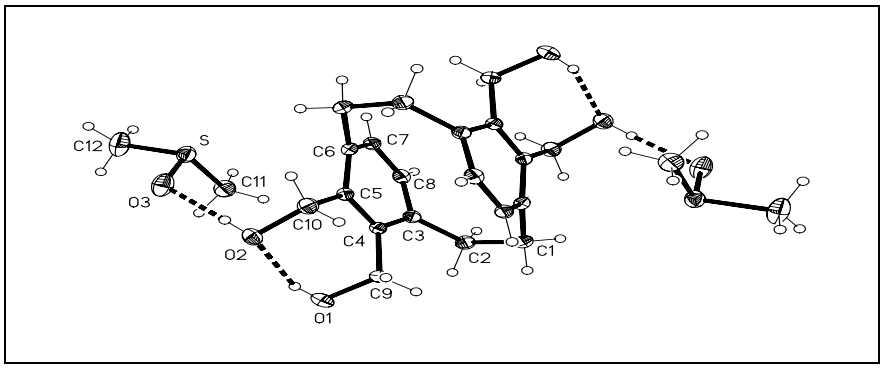
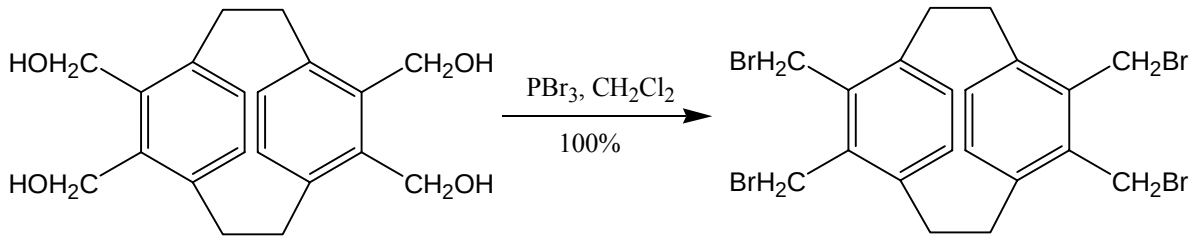


Fig. 13. Structure of 4,5,12,13-tetrakis(hydroxymethyl)[2.2]paracyclophane (**98**) in the crystal.

Although known, **28** still remains an elusive goal. Clearly before the reactive behaviour of this interesting cyclophane derivative can be studied, its preparative access must be improved.

2.5.3 Reactions of 4,5,12,13-tetrakis(bromomethyl)[2.2]paracyclophane (99)

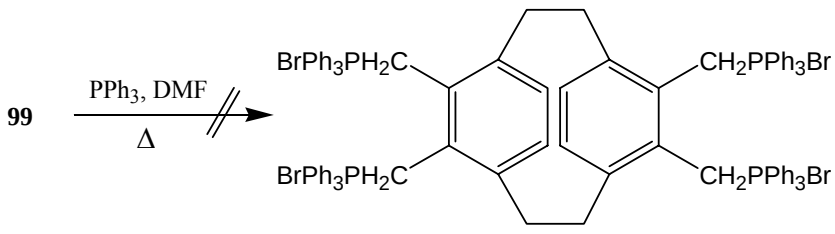
The tetrabromo derivative **99** is of importance since it can in principle be transformed to the corresponding tetrabromophosphonium salt which by various Wittig and carbonyl condensation reactions offers itself as a starting material for the synthesis of various annulated carbo- and heterocyclic ring systems. Subjection of 4,5,12,13-tetrakis(hydroxymethyl)[2.2]-paracyclophane (**98**) to bromination using phosphorous tribromide in dichloromethane as solvent under icecold conditions produced 4,5,12,13-tetrakis(bromomethyl)[2.2]-paracyclophane (**99**)[40] quantitatively.



98 **99**

Scheme 57. Synthesis of 4,5,12,13-tetrakis(bromomethyl)[2.2]paracyclophane (**99**).

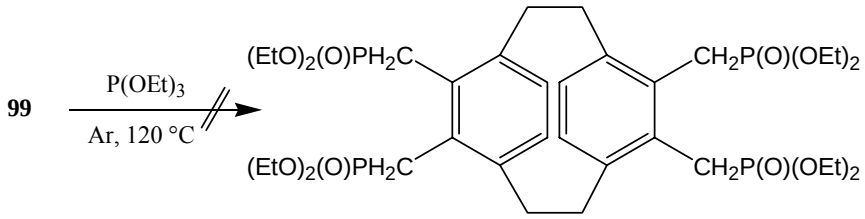
The procedure adopted to prepare the phosphonium salt was similar to that used for the conversion of 2,3-bis(bromomethyl)naphthalene to the corresponding bisphosphonium salt.[41] Treatment of compound **99** with triphenylphosphine in DMF under reflux for 6 hours resulted only in the recovery of the starting material (Scheme 58). Extending the reaction time had no characteristic effect and the starting material was recovered as such.



100

Scheme 58. Attempted synthesis of **100**.

In the search to find a good substrate for the synthesis of the desired cyclic compounds, a Horner-Emmons coupling precursor namely 4,5,12,13-tetrakis(diethylphosphonatemethyl)-[2.2]paracyclophane (**101**) was put forth, as normally phosphonate esters exhibit good solubility and the reaction byproducts are water soluble and enable simpler purification techniques. The synthetic procedure i.e. Arbuzov reaction was similar to the synthesis of the corresponding *crossed*-tetraphosphonate ester isomer.[42] Treatment of compound **99** with triethyl phosphite under argon at 120 °C over a period of 2 h resulted in a brown solid. The compound was highly insoluble, hence none of the spectroscopic characterisations could be carried out. The mass spectra revealed the presence of a complex mixture of compounds. Due to this complexity further reactions could not be carried out.

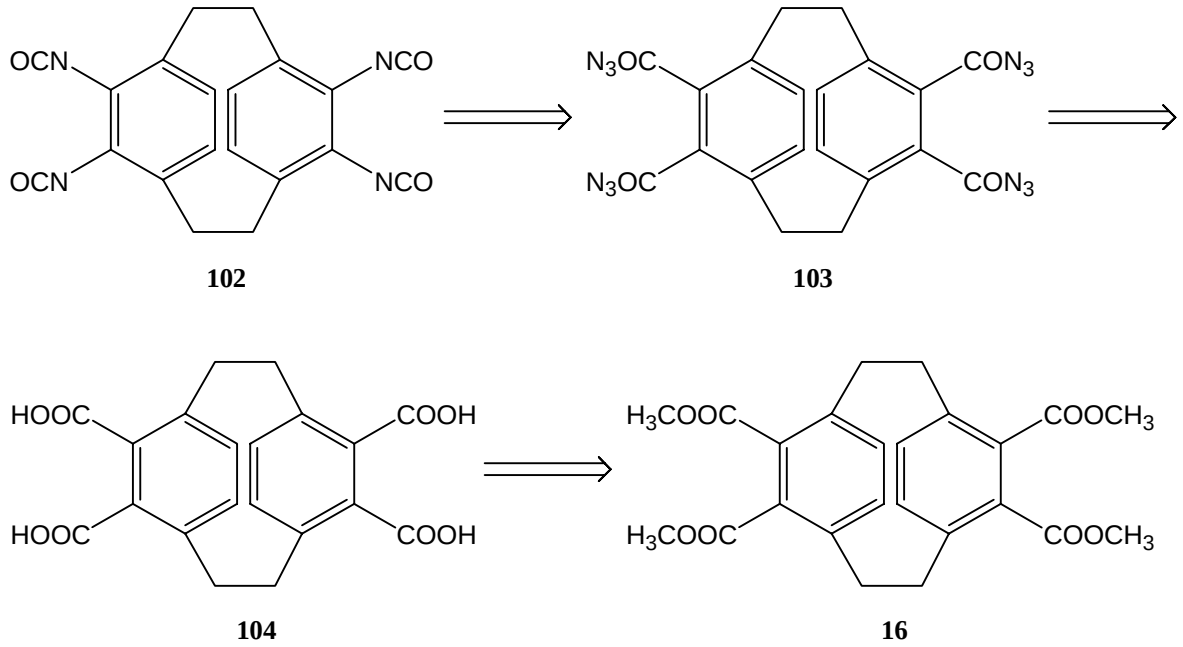


101

Scheme 59. Attempted synthesis of 4,5,12,13-tetrakis(diethylphosphonatemethyl)[2.2]-paracyclophane (**101**).

2.5.4 Reactions of 4,5,12,13-tetrakis(methoxycarbonyl)[2.2]paracyclophane (16)

Concerning 4,5,12,13-tetraisocyanato[2.2]paracyclophane (**102**), which could prove to be a useful starting material for polymerisation by CVD, retro synthetic analysis reveals that it could be realised by Curtius rearrangement from the corresponding azidocarbonyl derivative **103** which, in turn, could be synthesised from the corresponding tetracarboxy[2.2]-paracyclophane (**104**) available from the corresponding methyl ester **16** by means of saponification (Scheme 60).

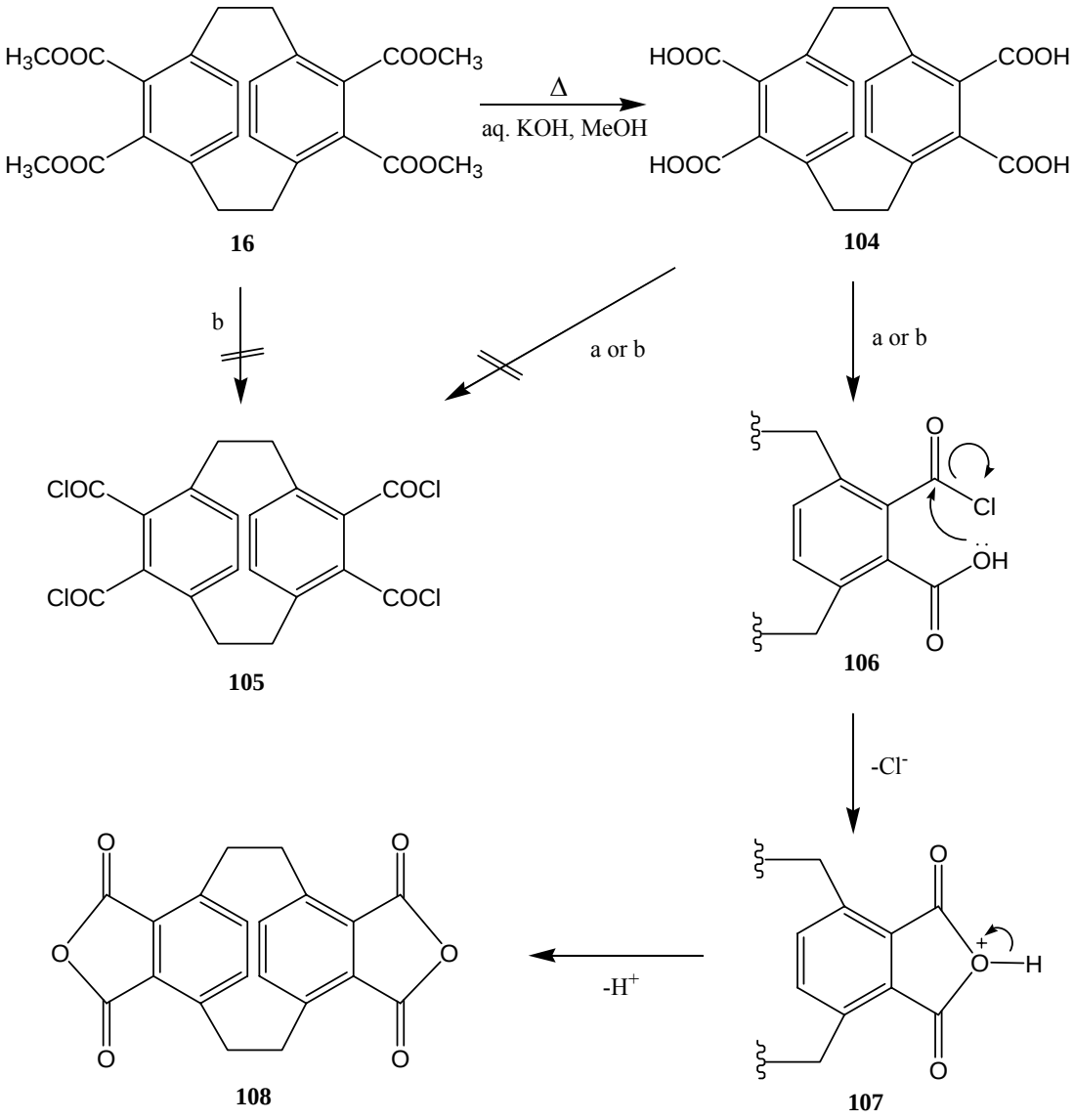


102 **103** **104** **16**

Scheme 60. Retrosynthesis for 4,5,12,13-tetraisocyanato[2.2]paracyclophane (**102**).

Saponification of 4,5,12,13-tetrakis(methoxycarbonyl)[2.2]paracyclophane (**16**) with aq. KOH solution in methanol under reflux over two weeks produced 4,5,12,13-tetracarboxy[2.2]paracyclophane (**104**) upon acidification with 2N aq. HCl, quantitatively. Treatment of **104** with thionyl chloride in the presence of DMF under reflux lead to the corresponding anhydride **108** rather than the expected 4,5,12,13-tetrakis(chlorocarbonyl)[2.2]paracyclophane (**105**).

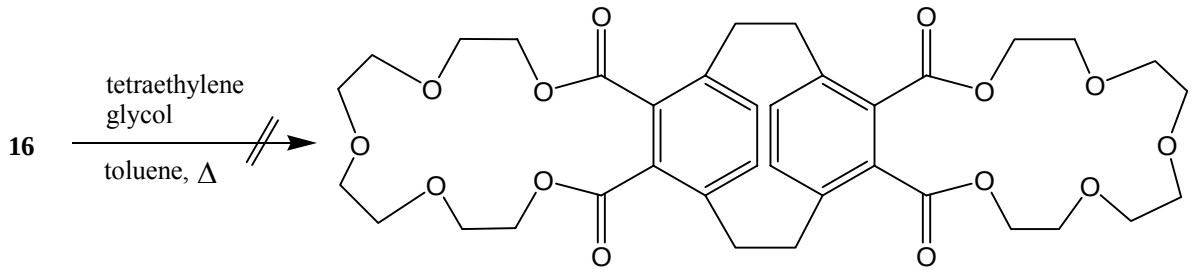
Hence milder reaction conditions were adopted by using oxalyl chloride in dichloromethane in the presence of DMF as catalyst at room temperature. Even under such conditions, the process resulted in the formation of the anhydride **108** as the only product (Scheme 61). Evidently, the formation of **108** is more feasible and it can be explained by the proximity of carboxyl function. The introduction of the chloride presumably takes place in a stepwise manner and once one of the carboxyl is transformed to the corresponding acid chloride, the neighbouring acid moiety attacks the acid chloride in an intramolecular fashion resulting in the formation of the anhydride. When **16** was treated with oxalyl chloride in anhydrous dichloromethane in the presence of 10% v/v mixture of DMF/dichloromethane as a catalyst at room temperature no characteristic reaction was observed, and the starting material was recovered as such.



a) $SOCl_2$, DMF, reflux; b) $(COCl)_2$, DMF, dry CH_2Cl_2, room temperature.

Scheme 61. Attempted synthesis of 4,5,12,13-tetrakis(chlorocarbonyl)[2.2]paracyclophane (**105**).

Transesterification of compound **16** with glycol ethers like tetraethylene glycol may lead to the formation of bis(crownether)-phanes such as **109**. However, when compound **16** was subjected to treatment with tetraethylene glycol in toluene no identifiable conversion took place. The reaction was monitored by thin layer chromatography (TLC), which revealed that no characteristic reaction took place (Scheme 62).



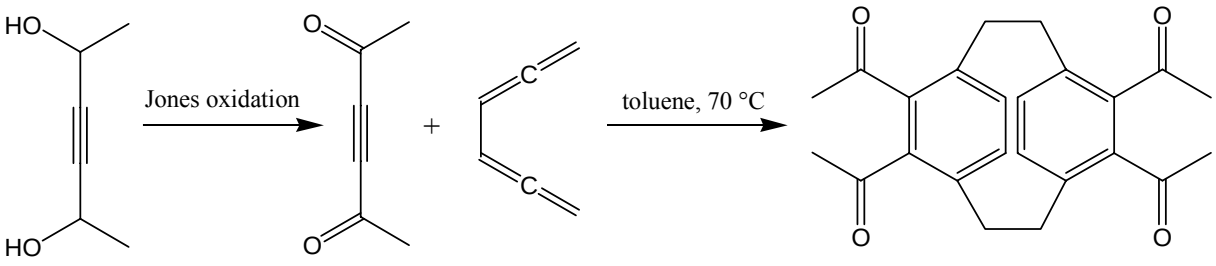
109

Scheme 62. Attempted *trans*-esterification of compound **16**.

2.5.5 4,5,12,13-Tetraacetyl[2.2]paracyclophane (30)

As already mentioned, tetraacetyl phane **30** could prove to be an interesting starting material for various carbonyl condensation reactions and further derivatisations. 4,5,12,13-Tetraacetyl[2.2]paracyclophane (**30**) was obtained by cycloaddition of bisallene **92** to hex-3-yne-2,5-dione (**111**)[43] in 12% yield as colourless crystalline solid (Scheme 63). The synthesis of dione **111** was similar to that reported in the literature by means of Jones oxidation of the corresponding diol **110**, but with slight modification as discussed in the experimental section under 4.2.22.

In the ^{1}H NMR spectrum of **30**, two sharp singlets appear at δ = 6.75 (4 H) and 2.32 (12 H) corresponding to the aromatic and the methyl protons, respectively. In the ^{13}C NMR spectrum the carbonyl carbon atom appears at δ = 203.4 and in the IR spectrum the carbonyl moiety displays a strong absorption band at 1688 cm^{-1}. In the EI mass spectrum the molecular ion peak appears at *m/z* = 376 which undergoes fragmentation by losing a methyl group to give *m/z* = 361.



110 **111** **92** **30** (12%)

Scheme 63. Synthesis of 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**).

Tablet-shaped crystals of X-ray quality were obtained by slow diffusion of pentane to a saturated solution of **30** in dichloromethane. The molecule crystallises in $P2_1/c$, monoclinic unit cell. The compound exhibits two different types of packing and hence, there are two different types of molecules, and both possess inversion symmetry. The tetraacetyl phane **30** has a complex 3-D packing with four C-H…O and one C-H…π hydrogen bonds [C(12')-H(12D)...O(1) (2.63 Å), C(10')-H(10E)...O(2) (2.55 Å), C(12)-H(12C)...O(2') (2.45 Å), C(1)-H(1A)...O(2') (2.67 Å)].

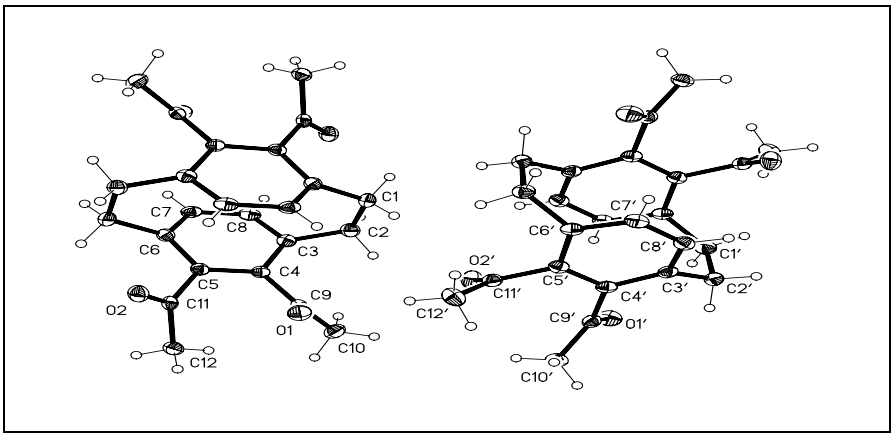
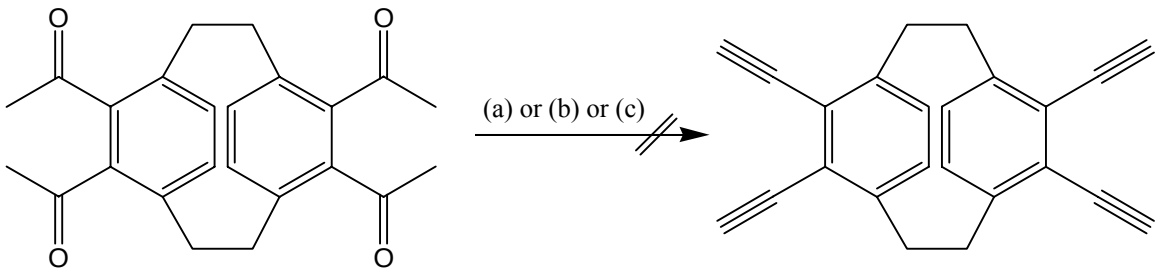


Fig. 14. Structure of 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**) in the crystal.

2.5.6 Reactions of 4,5,12,13-tetraacetyl[2.2]paracyclophane (30)

Several attempts to synthesise 4,5,12,13-tetraethynyl[2.2]paracyclophane (**32**) by means of metal coupling reactions (Sonogashira reaction) from the corresponding halo derivatives failed. Hence it was proposed that **32** could be realised by the conversion of the keto functionality of **30** to the corresponding dihalo derivative, which on further treatment with base could yield the desired compound.



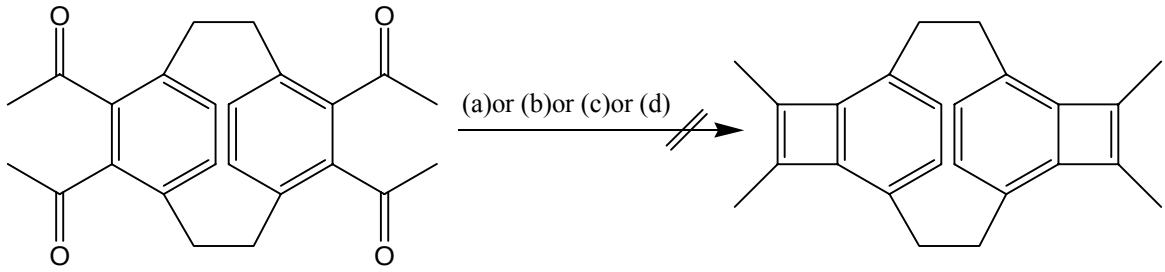
30 **32**

a) PCl_5, benzene; b) PCl_5, benzene, pyridine, reflux; c) LDA, $ClP(O)(OEt)_2$, THF, -78 °C, Ar.

Scheme 64. Attempted synthesis of 4,5,12,13-tetraethynyl[2.2]paracyclophane (**32**).

However, subjection of **30** to halogenation using phosphorous pentachloride in benzene resulted in the decomposition of the starting material. A one step synthesis of acetylenes from ketones was described by Wong *et al.*[44] A similar procedure was adopted for **30** which was added slowly to a mixture of PCl_5, anhydrous pyridine and anhydrous benzene at 40 °C in one portion. After the mixture had been subjected to reflux for 3 hours, the reaction was quenched by the addition of ice cold water, on work up only a dark brown intractable material could be isolated. The decomposition of the paracyclophane moiety may be due to the harsh conditions, namely the use of PCl_5 as halogenating agent. In 1980 Negishi used LDA and diethyl chlorophosphate for the conversion of some methyl ketones to terminal acetylenes.[45] Treatment of **30** with LDA and diethyl chlorophosphate at -78 °C resulted in the loss of the starting material and recovery of an intractable dark brown sticky solid (Scheme 64). In all the above reactions the paracyclophane skeleton was lost (from the ^1H NMR analysis of the crude material) and no characteristic products could be isolated.

Recently Stanger *et al.* have published,[46] theoretical calculations, that dicyclobutano and dicyclobutadieno[2.2]paracyclophanes, though highly strained molecules, should exist. Immediately it was envisaged that the teraacetyl phane **30** when subjected to McMurry coupling could yield the desired methyl substituted dicyclobutadieno[2.2]paracyclophane (**31**).

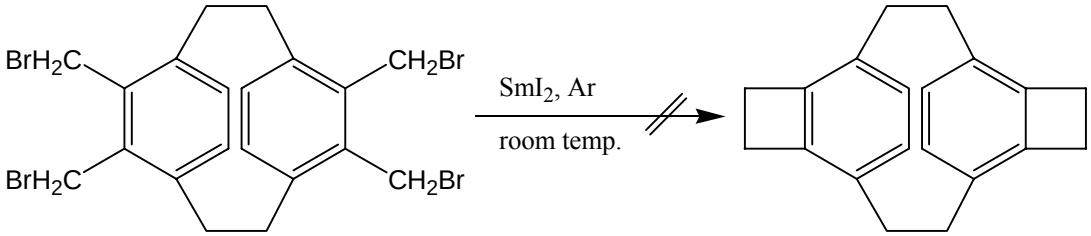


30 **31**

a) $TiCl_3$, Zn-Cu couple, DME, Ar, reflux; b) $TiCl_4$, pyridine, Zn, -78 °C; c) $TiCl_4$, Zn, THF, $Fe_2(CO)_9$; d) $TiCl_4$, Zn, pyridine, $Fe_2(CO)_9$.

Scheme 65. Attempted synthesis of dicyclobutadieno[2.2]paracyclophane (**31**).

However various coupling reactions and also an attempt to trap the molecule *in situ* by using $Fe_2(CO)_9$ as shown in Scheme 65, failed. Clearly, the theoretically possible hydrocarbon, under practical experimental conditions still remains a dream.

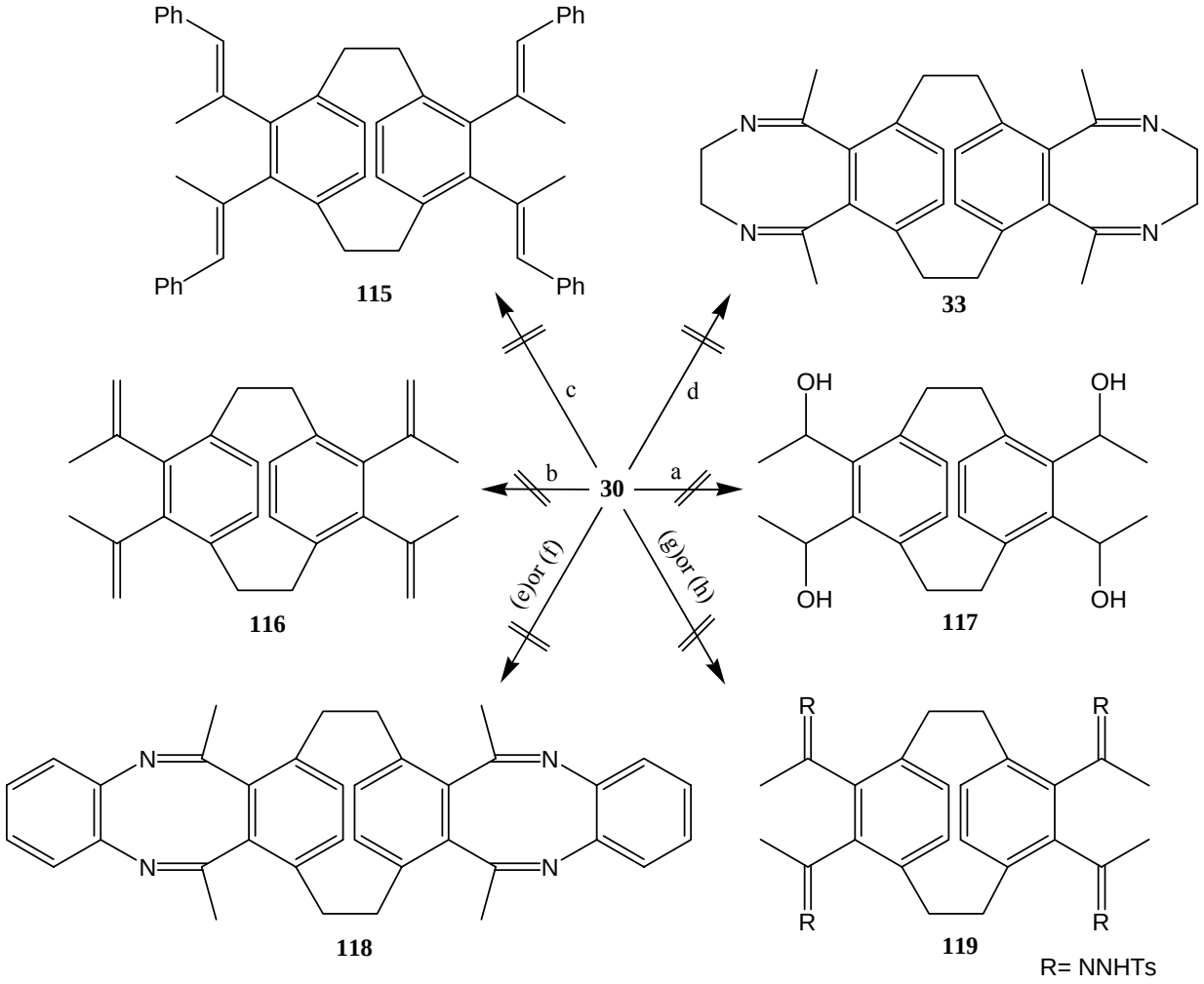


99 **112**

Scheme 66. Samarium iodide induced coupling reaction of 4,5,12,13-tetrakis(bromomethyl)-[2.2]paracyclophane (**99**).

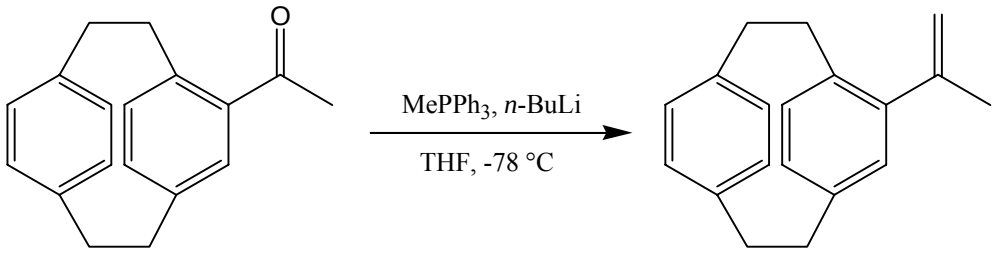
Since samarium iodide induced coupling reactions have been used to synthesise cyclophanes,[47] a similar protocol was used in an attempt to prepare dicyclobutano[2.2]paracyclophane (**112**). Treatment of 4,5,12,13-tetrakis(bromomethyl)[2.2]-paracyclophane (**99**) with 0.1 M solution of SmI_2 in THF under argon at room temperature produced an off-white, highly insoluble solid (Scheme 66). Spectroscopic analysis of the compound was impossible due to the highly insoluble nature of the product in the common organic solvents.

Reduction of **30** using $LiAlH_4$ in THF under reflux, resulted in the loss of the starting material, but no characteristic product was isolated. To explore the feasibility of various carbonyl condensation, Wittig reactions and hetero annulation reactions of the tetraacetyl phane **30**, different C-C bond forming reactions were carried out. Treatment of compound **30** under standard Wittig reaction conditions with methyl phosphoniumbromide or phenylphosphoniumbromide at -78 °C in THF did not afford the corresponding products **116** and **115,** respectively (Scheme 67). As a matter of fact no defined product could be isolated from the reaction mixture. The reason may be that the acetyl groups are enolisable and may have undergone oligo- or polymerisation under basic conditions. Condensation of tetraacetyl phane with amines would lead to heterocyclic systems or hydrazone derivatives. Ethylenediamine, *ortho*-phenylenediamine,[48] tosylhydrazine were exposed to compound **30** under various reaction conditions (Scheme 67) expecting the corresponding heterocyclic and hydrazone derivatives. Unfortunately, all these reactions resulted in the formation of a dark blue intractable solid.



a) LAH, THF, reflux; b) $MePPh_3Br$, *n*-BuLi, THF, -78 °C; c) $PhPPh_3Br$, *n*-BuLi, THF, -78 °C; d) ethylene diamine, $TiCl_4$, toluene; e) *ortho*-phenylenediamine, $TiCl_4$, toluene; f) *ortho*-phenylenediamine, abs. ethanol, reflux; g) *ortho*-phenylenediamine, $TiCl_4$, toluene; h) *ortho*-phenylenediamine, acetic acid.

Scheme 67. Attempted transformations of 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**).



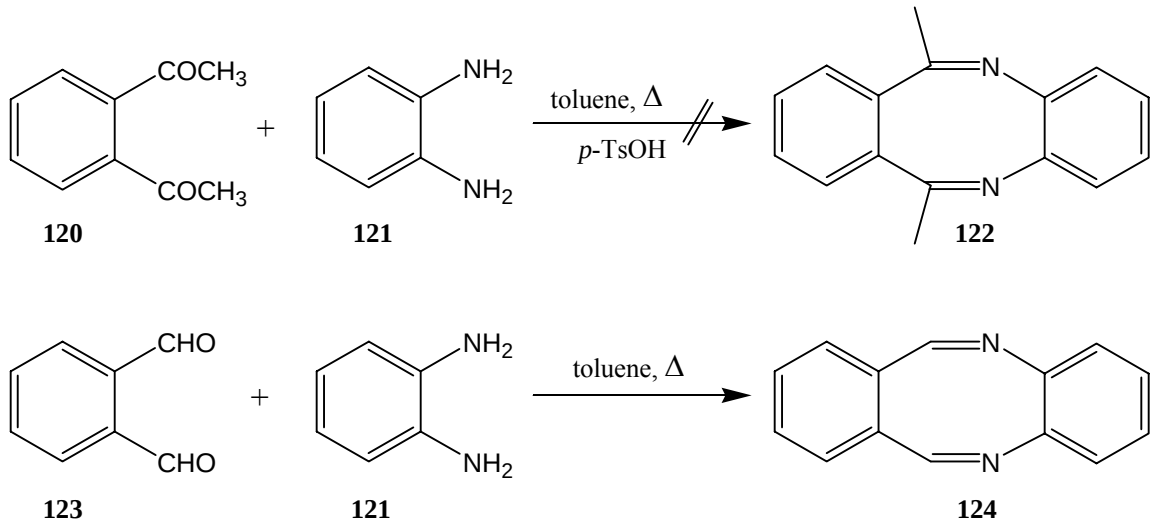
113 **114**

Scheme 68. Synthesis of 4-isopropenyl[2.2]paracyclophane (**114**).

As a test reaction 4-acetyl[2.2]paracyclophane (**113**) was subjected to Wittig olefination using $MePPh_3Br$ and *n*-BuLi in THF at -78 °C to yield 4-isopropenyl[2.2]paracyclophane (**114**) in

40% yield (Scheme 68).[66] For a cyclophane, **114** exhibits a very low melting point (50 °C) and the structure follows from its spectroscopic data.

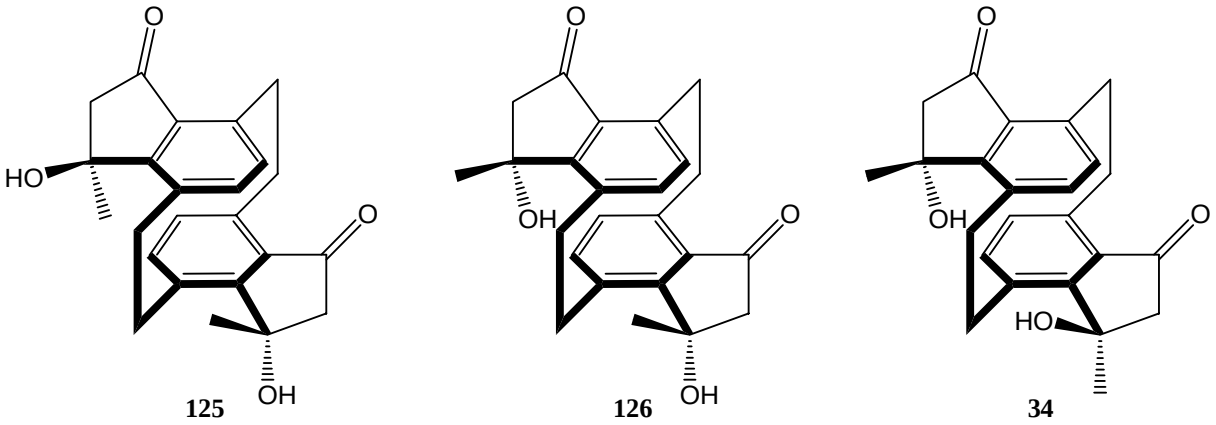
To analyse these results model reactions were carried out using 1,2-diacetylbenzene (**120**) and 1,2-diformylbenzene (**123**) with *ortho*-phenylenediamine (**121**) in refluxing toluene (Scheme 69). Compound **123** reacted readily to yield the corresponding heterocyclic compound **124** (analysed by GC-MS, [M^+] 206), whereas diacetylbenzene **120** did not provide the desired compound **122**. It can hence be concluded that the aldehyde functionality is more prone to amine condensation reactions than the keto group.



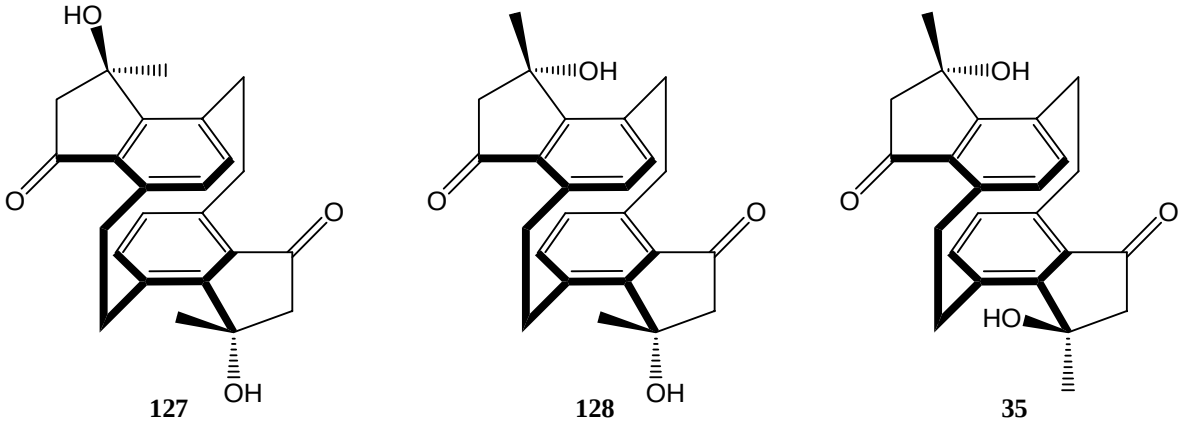
Scheme 69. Condensation reactions using *ortho*-phenylenediamine (**121**).

2.5.7 Aldol condensation of 4,5,12,13-tetraacetyl[2.2]paracyclophane (30)

In principle the aldol condensation of 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**) would lead to the formation of six different chiral isomers in terms of the orientation of the carbonyl moiety and the hydroxyl functionality. The carbonyl moiety can be oriented on the same side (*syn*) or opposite to each other (*anti*) giving rise to two different regioisomers. Among these two types the hydroxyl functionality can be oriented either towards the cyclophane cavity (*endo*) or away from it (*exo*), hence giving rise to six different isomers. The structures of the isomers are summarized in Scheme 70.



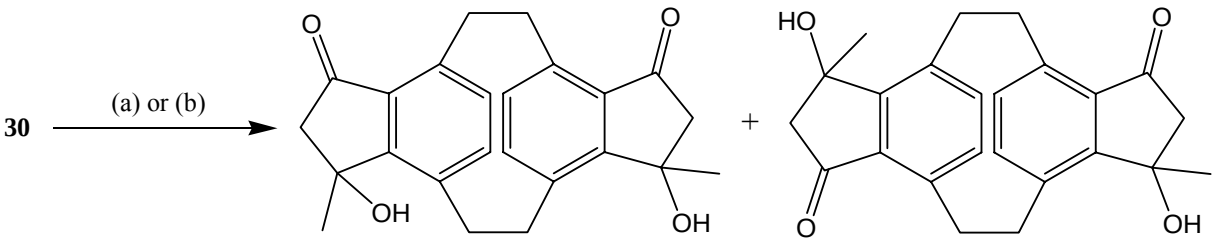
125 (*syn*, *exo*, *exo*) **126** (*syn, exo*, *endo*) **34** (*syn, endo*, *endo*)



127 (*anti*, *exo*, *exo*) **128** (*anti, exo*, *endo*) **35** (*anti, endo*, *endo*)

Scheme 70. Possible six regioisomers of the aldol reaction of 4,5,12,13-tetraacetyl-[2.2]paracyclophane (**30**).

Subjecting 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**) to aldol condensation in the presence of a base produces exclusively compounds **34** and **35** in 30% and 70% yields, respectively. The *anti* isomer **35** is relatively insoluble and can be separated from the reaction mixture by means of simple filtration. The structures of **34** and **35** follow from their spectroscopic data, in particular from an X-ray crystallographic analysis of **34**.



34 **35**

a) NaOH, abs. methanol, room temperature; b) aniline, abs. methanol, room temperature.

Scheme 71. Aldol reaction of 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**).

The exclusive formation of compounds **34** and **35** with (*endo*,*endo*)-conformation of the hydroxyl groups can be explained from the X-ray structure of compound **30**, where all the carbonyl groups are facing towards the cavity of the phane. It has been observed in the case of 4-acetyl[2.2]paracyclophane (**113**), that the keto group has *endo* conformation in the crystal state and also in solution (proved by NMR studies).[59] The same can be assumed for compound **30** in solution and hence leading to the exclusive aldol products.

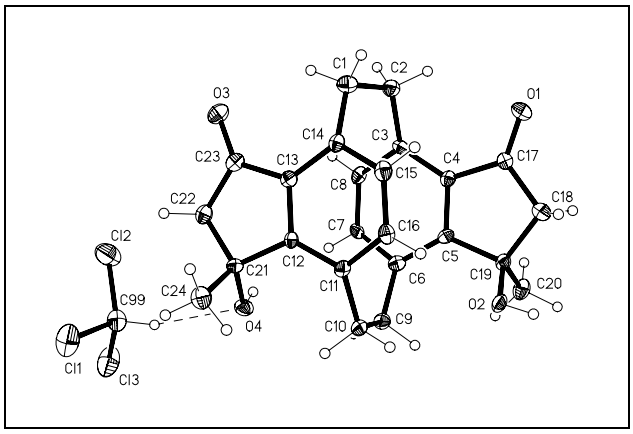


Fig. 15. Structure of *syn*(*endo*,*endo*)-19,21-dihydroxy-19,21-dimethyl[2.2]indanonophane-17,23-dione (**34**) in the crystal.

Plate-shaped crystals of X-ray quality were obtained by slow evaporation of a solution of **34** in chloroform. The compound crystallises in $Pca2_1$, orthorhombic unit cell and displays strong hydrogen bonds with the solvent molecule, namely chloroform. A look into the packing diagram shows that the molecules are arranged in sheet like fashion (cyclophane-chloroform-cyclophane) with eight different hydrogen bonds involved in it [O(2)-H(2)...O(1) (1.98 Å), O(4)-H(04)...O(3) (2.13 Å), C(24)-H(24B)...O(2) (2.54 Å), C(7)-H(7)...O(3) (2.36 Å), C(22)-H(22A)...Cl(2) (2.96 Å), C(18)-H(18A)...Cl(3) (2.96 Å), C(22)-H(22B)...Cl(3) (2.78 Å), C(99)-H(99)...O(4) (2.50 Å)] (Fig. 15 and 16).

Several attempts to crystallise the *anti* isomer **35** failed. Gas phase geometrical optimisation by DFT calculations (B3LYP/6-31G(d) programme) reveal that compounds **34** and **35** differ by ± 0.01 kcal/mol (Fig. 17). Also compound **35** having the (*endo*,*endo*) conformation was found to posses the least energy when compared to the other isomers **127** and **128**.

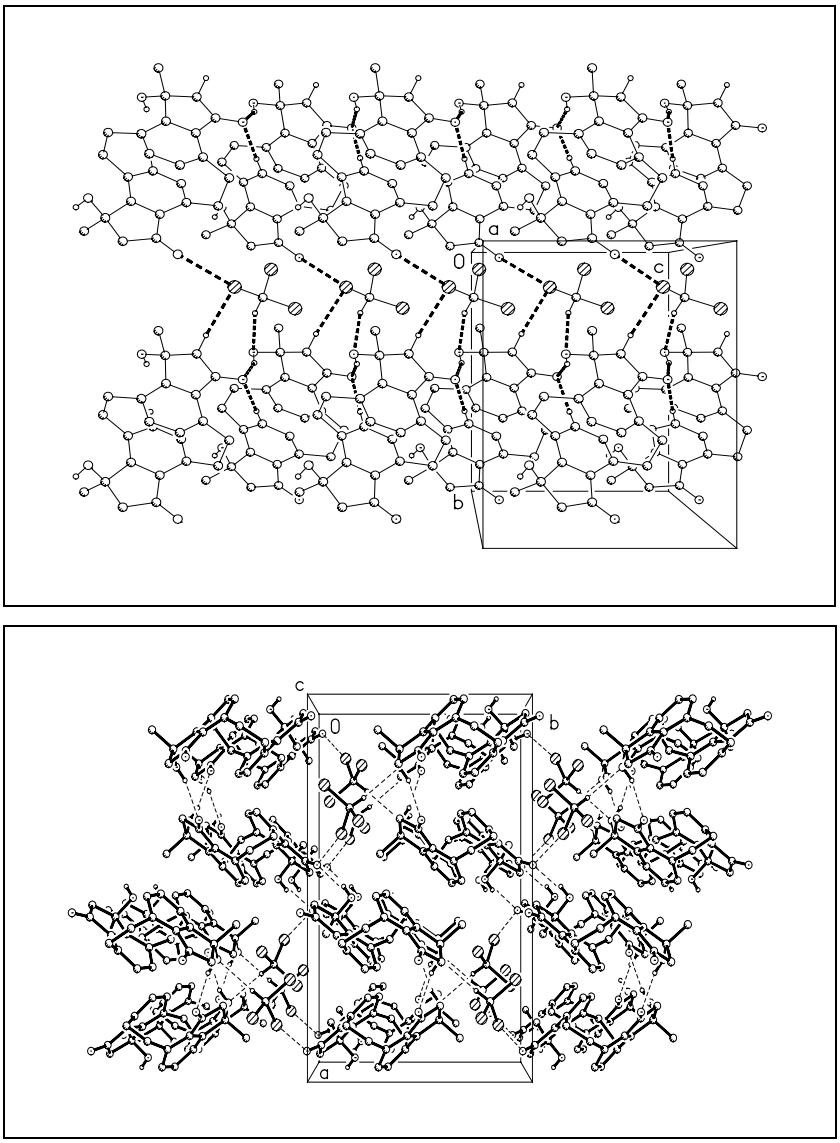


Fig. 16. Packing diagrams of *syn*(*endo*,*endo*)-19,21-dihydroxy-19,21-dimethyl[2.2]indanonophane-17,23-dione (**34**).

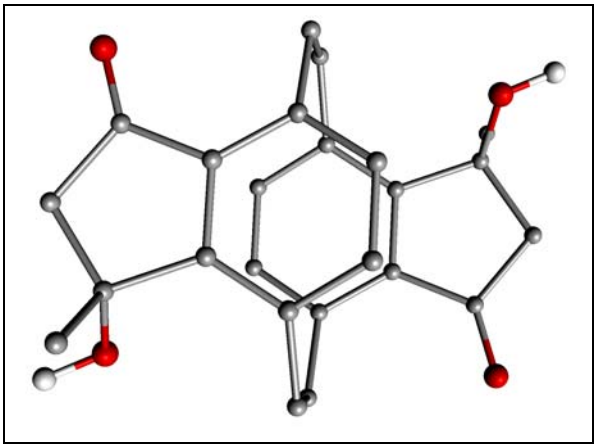
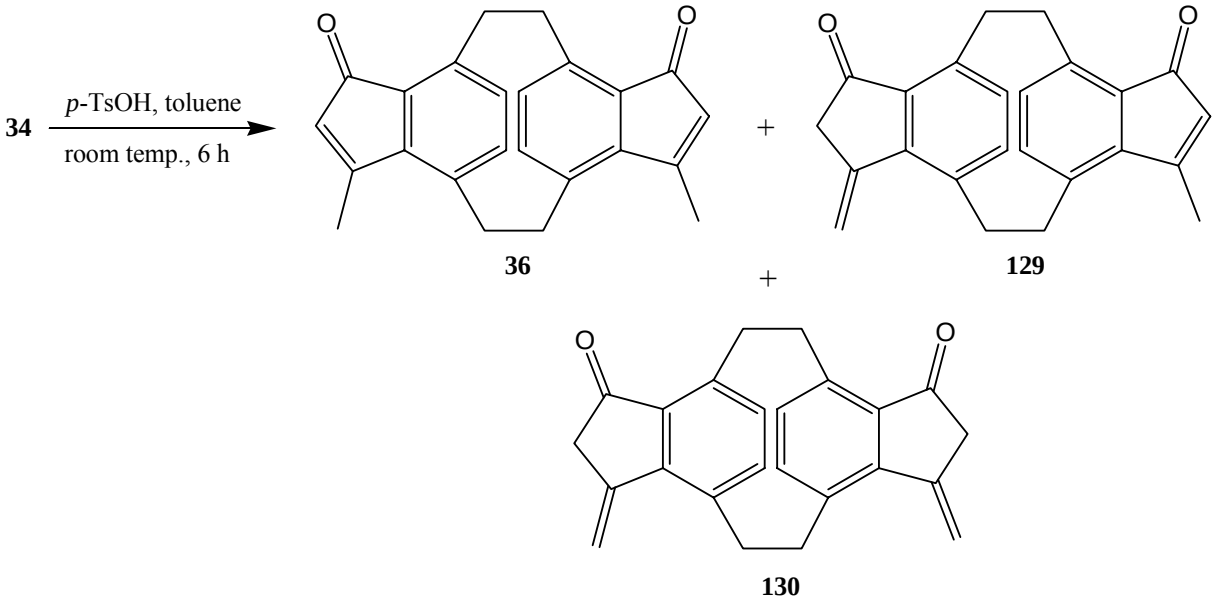


Fig. 17. B3LYP/6-31G(d) gas phase optimisation of *anti*(*endo*,*endo*)-19,23-dihydroxy-19,23-dimethyl[2.2]indanonophane-17,21-dione (**35**) starting with a C_i symmetry.

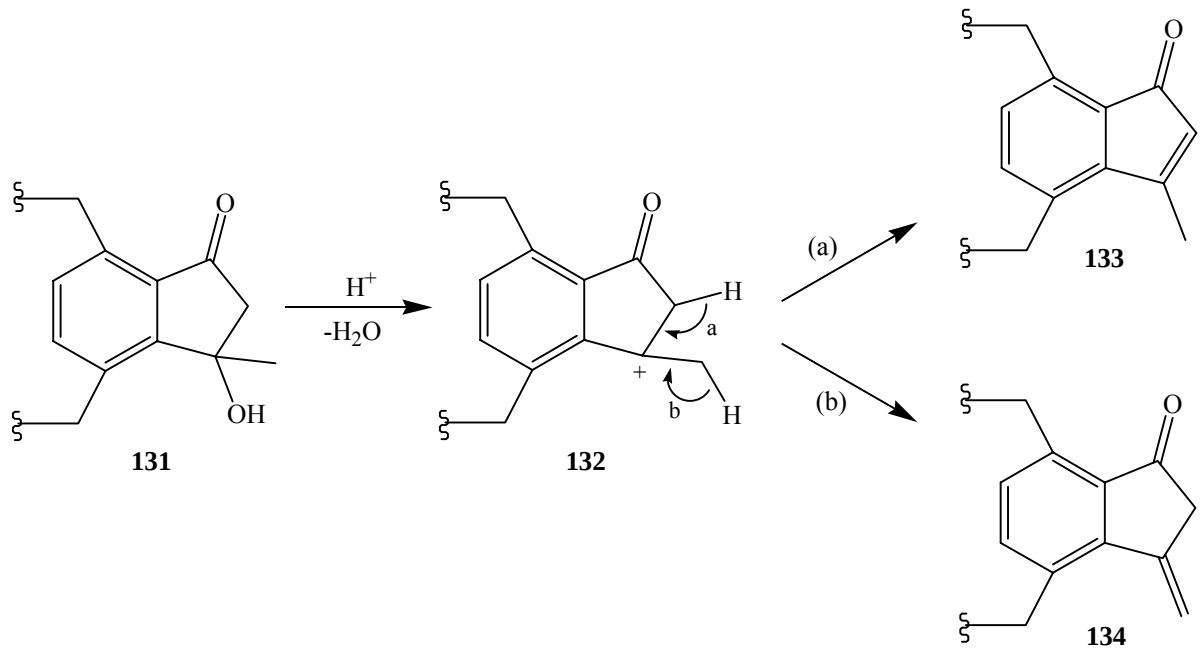
2.5.8 Synthesis of indenonophanes

Dehydration of compound **34** using catalytic amounts of *para*-toluenesulfonic acid in toluene at room temperature, followed by preparative thin layer separation after several repeated elutions with 1% EtOAc in CH_2Cl_2, produces indenonophanes **36**, **129** and **130** in 30, 30 and 37% yield, respectively.



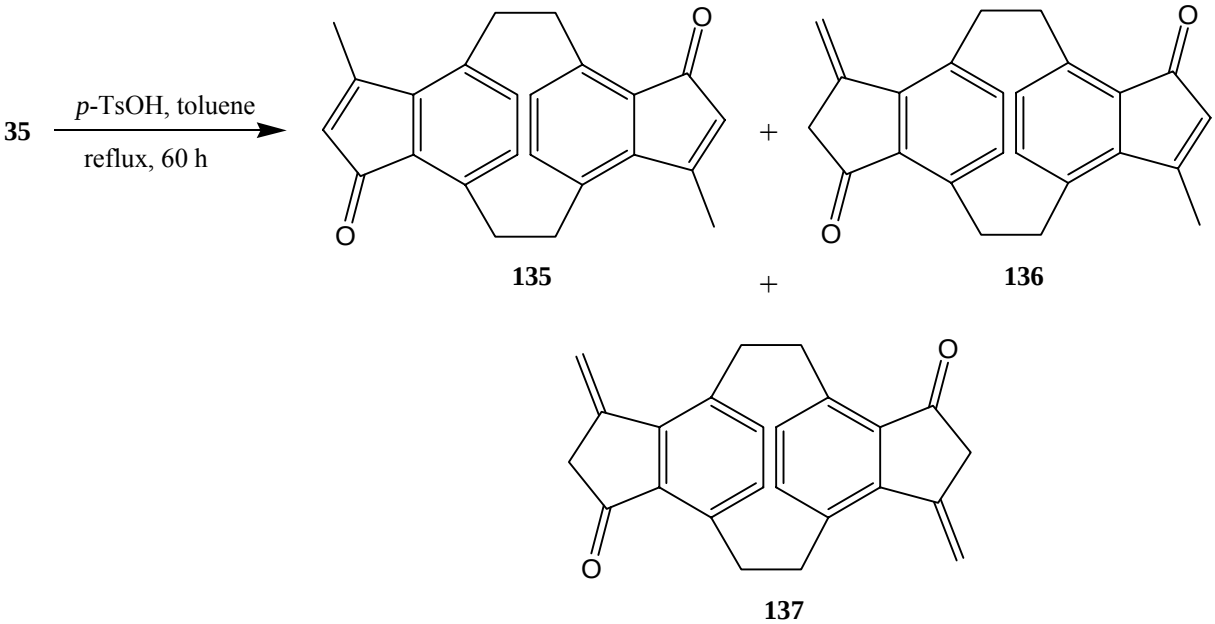
Scheme 72. Dehydration reaction of *syn*-19,21-dihydroxy-19,21-dimethyl[2.2]indanonophane -17,23-dione (**34**).

Compounds **36** and **129**, being highly conjugated systems are bright yellow in colour and have an absorption maximum of 363 and 350 nm in the UV/Visible region, whereas compound **130** is a colourless solid with an absorption maximum of 247 nm. In the ^{1}H NMR spectrum, the exocyclic methylene protons appear in the region δ = 5.79 and 5.39 as a singlet. In the IR spectrum, strong absorption bands due to the carbonyl moiety are registered in the region of 1690 cm^{-1}. As far as the mechanism of the dehydration process is concerned, the hydroxyl group is protonated first, enabling the loss of a water molecule and leading to the formation of a stable tertiary carbocation **132**. This can undergo hydrogen E_1 elimination by route (a) to give the α,β-unsaturated Zaitsev product **133** or by route (b) to give the exocyclic methylene Hofmann product **134** (Scheme 73).



Scheme 73. Mechanism of the dehydration process of indanonophanes **34** and **35**.

The pure *anti* isomer **35** was also subjected to dehydration using catalytic amounts of *p*-TsOH in dry toluene. The reaction was carried out under reflux for 60 h due to the insoluble nature of **35**. The dehydration leads to the formation of three isomers, similar to the dehydration of the *syn* isomer. Indenonophanes **135**, **136** and **137** were separated by preparative thin layer chromatography and were obtained in 16, 48 and 16% yields, respectively.



Scheme 74. Dehydration reaction of *anti*-19,23-dihydroxy-19,23-dimethyl[2.2]indanono-phane-17,21-dione (**35**).

Indenonophanes **135** and **136**, being highly conjugated α,β-unsaturated ketones, are bright yellow solids having UV/Visible absorption maximum of 389 and 358 nm. Yellow tablet-shaped crystals of X-ray quality of indenonophane **135** were obtained by slow diffusion of pentane into a saturated solution of **135** in dichloromethane. **135** crystallises in *C2/c*, monoclinic unit cell and the bridge protons are intra molecularly hydrogen bonded with the oxygen atoms [C(1)-H(1B)...O (2.62 Å), C(10)-H(10)...O (2.67 Å)]. Also strikingly there are short intermolecular contacts from hydrogen atoms of the methyl groups to the centroids of the aromatic rings [C(12)-H(12A)…Cg (2.63 Å, 147°)].

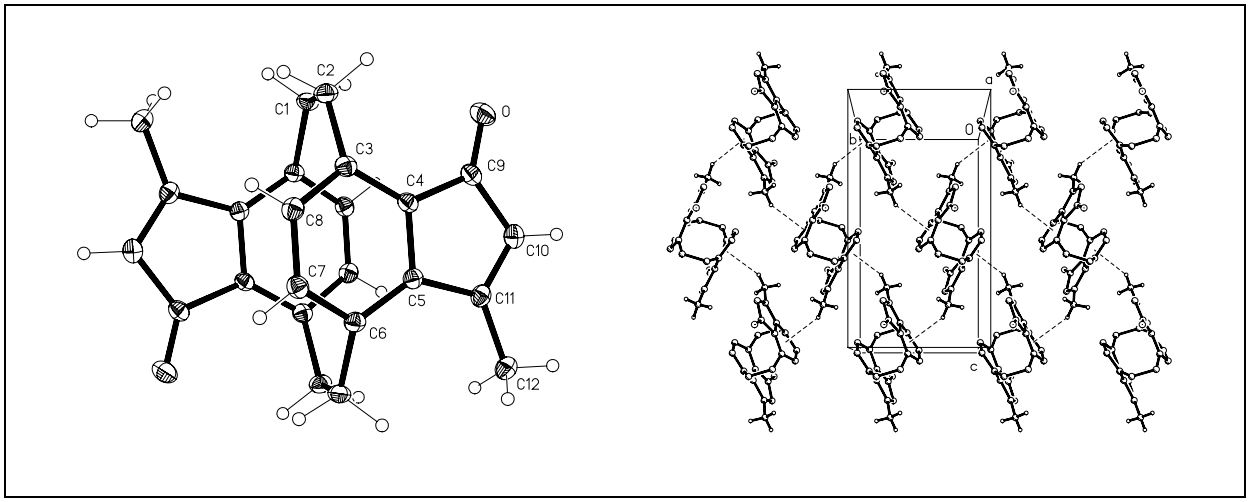
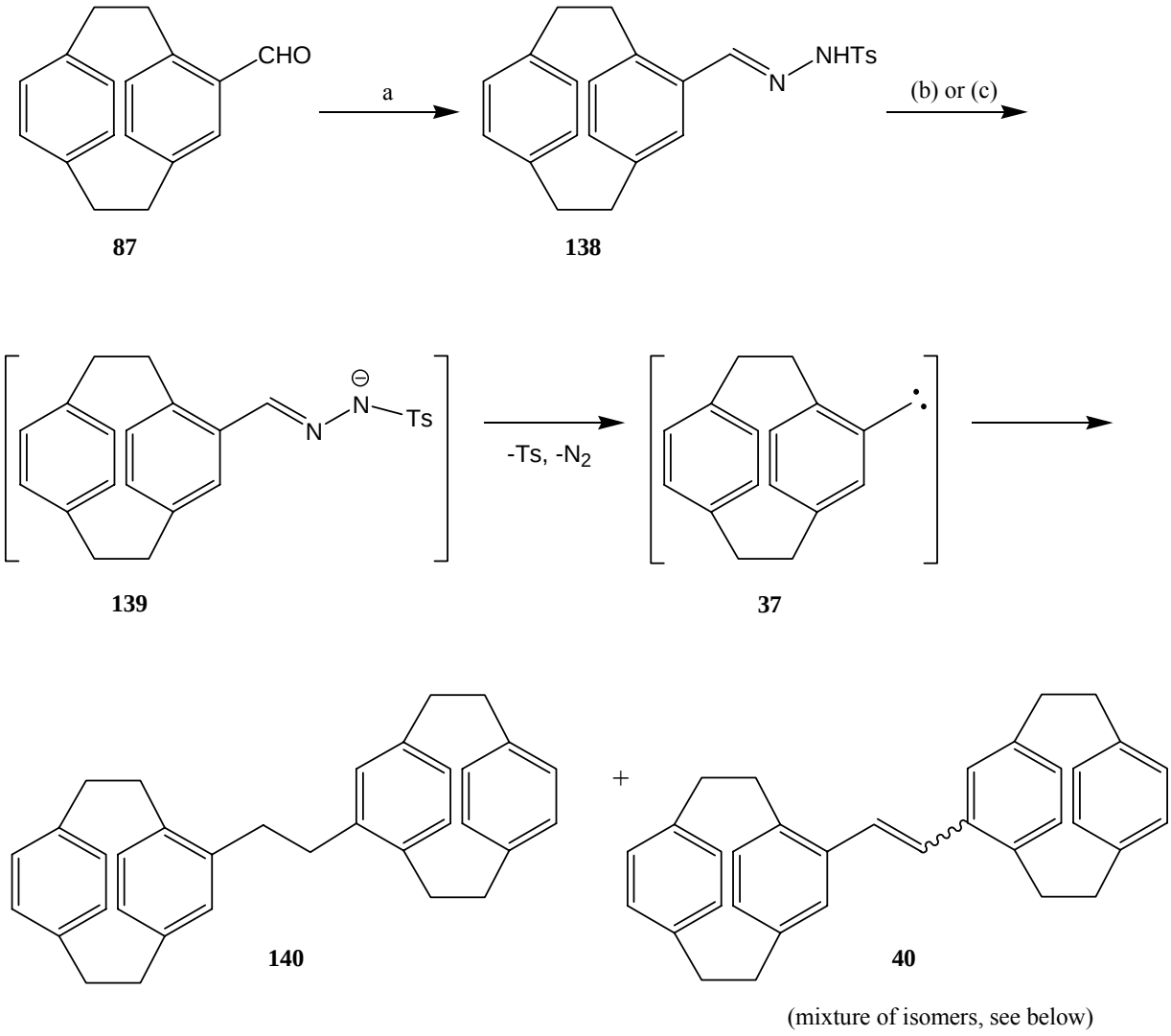


Fig. 18. Crystal structure and packing diagram of *anti*-19,23-dimethyl[2.2]indenonophane-17,21-dione (**135**).

2.6 Carbene reactions

There are several ways to generate carbenes *in situ*. A popular one consists in the treatment of a hydrazone under basic conditions at high temperatures in aprotic solvents, the so called Bamford-Stevens reaction. Treatment of 4-formyl[2.2]paracyclophane (**87**) with tosyl hydrazine in the presence of a catalytic amount of *p*-TsOH in toluene under reflux produced the desired hydrazone derivative **138** as a colourless solid quantitatively. When **138** was refluxed in diglyme, in the presence of a base, either *t*-BuOK or NaOMe, a mixture of compounds **140** and **40** was produced in 11% combined yield (Scheme 75).[49] As the reaction proceeds, the colour of the reaction mixture turns from clear golden yellow to turbid red. As far as the mechanism of the reaction is concerned, the base first abstracts the amine proton creating a negative charge on the nitrogen atom, which leads to the cleavage of the tosyl

group and further to the loss of the nitrogen molecule resulting in the formation of the carbene intermediate **37**. Two such carbene intermediates react to give **140** and **40**.

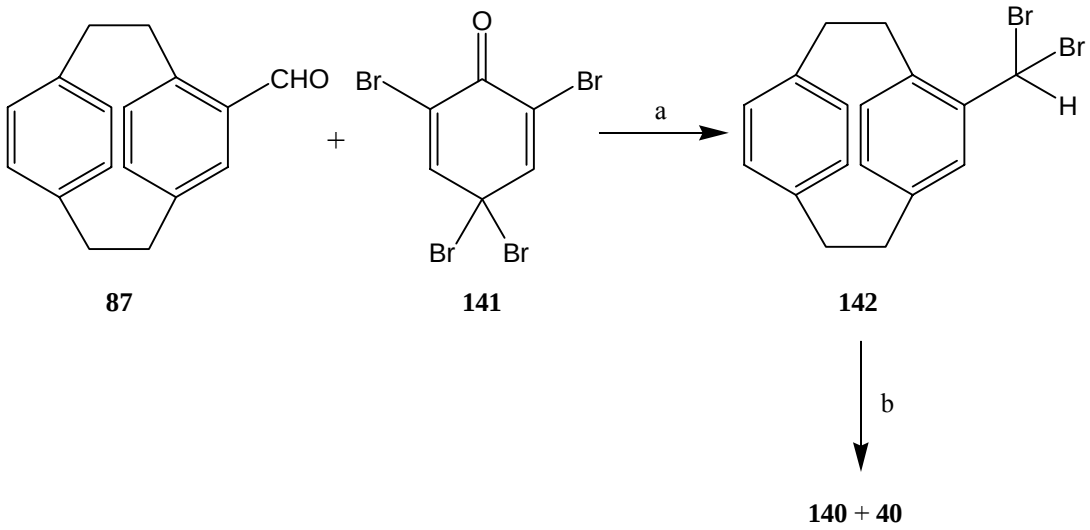


a) *p*-TsNHNH$_2$, *p*-TsOH, THF, reflux; b) *t*-BuOK, diglyme, reflux; c) NaOMe, diglyme, reflux.

Scheme 75. Synthesis of **140** and **40**.

In order to make sure that such generated carbenes undergo only dimerisation and no other characteristic insertion reactions (see below), a different strategy was adopted to generate the carbenes. 4-Formyl[2.2]paracyclophane (**87**) was subjected to bromination using 2,4,4,6-tetrabromo-2,5-cyclohexadienone (**141**) in refluxing anhydrous benzene in the presence of triphenylphosphine to produce 4-(1,1-dibromomethyl)[2.2]paracyclophane (**142**).[50] **142** was highly unstable and was used as such, without further purification, immediately for the next reaction. Exposure of an ethereal solution of **142** to zinc powder again produced the dimers **140** and **40** (combined yield 2%) as a mixture of colourless solids (Scheme 76), substantiating

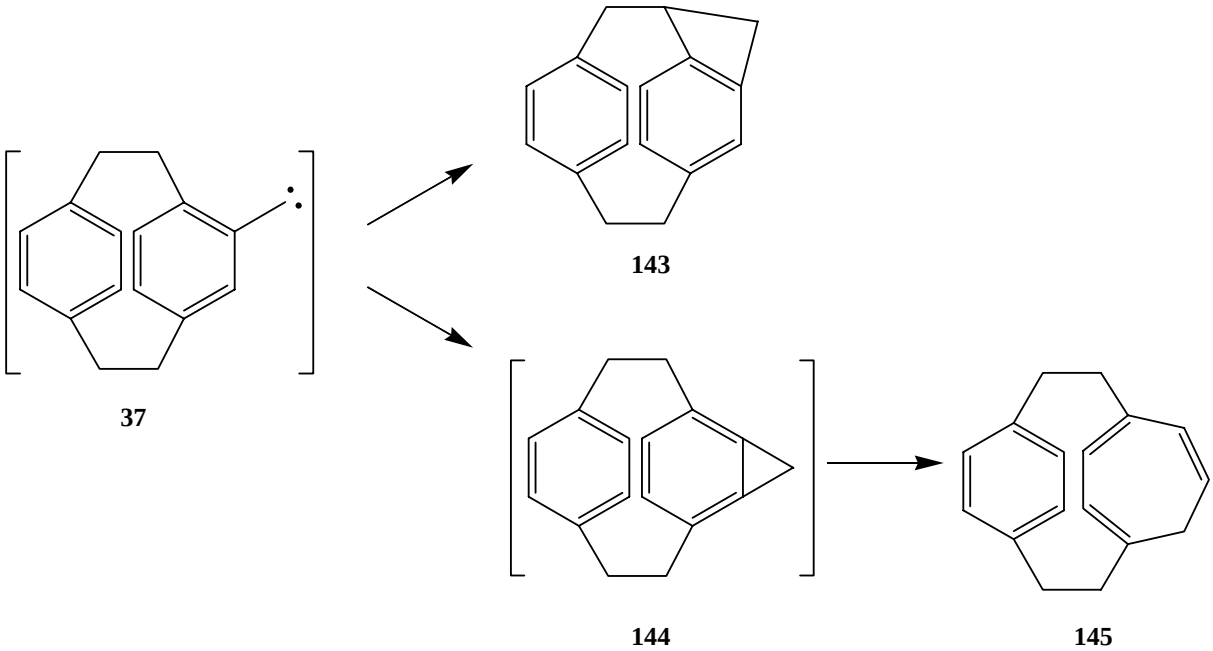
the previous result, that the carbene intermediate **37** (Section 1.4.5) undergoes preferentially dimerisation or intermolecular reaction than an intramolecular reaction.



a) PPh_3, benzene, Ar, reflux; b) Zn powder, ether, room temperature (24 h)→ reflux (4 h).

Scheme 76. Alternative way of generation of **140** and **40**.

Actually, there are several intramolecular routes conceivable. For example the carbene **37** could insert into one of the bridge C-H-bond yielding hydrocarbon **143**. Formally this would be a [2.1]cyclobutanophane. It would not only be highly strained because of its very short methanobridge but also because it contains a four membered ring. Obviously this strain is too high to allow the formation of **143**.



Scheme 77. Possible intramolecular reactions of carbene **37**.

Alternatively, **37** could participate in a ring expansion reaction leading to the cycloheptatrienophane (**145**). **145** would have to be produced via the benzocyclopropene intermediate **144**. Although the conversion of phenyl carbene to cycloheptatriene is known,[60] the above route is not followed, again presumably because of excessive strain.

As a matter of fact, there are three stereo isomers [*meso*, (*R*, *R*), (*S*, *S*)] possible in the cases of **140** and **40** shown in Scheme 78 in *trans*-conformation/configuration.[63] It is clear from the crystal structure that **140** has *meso* (*S*, *R*) conformation and is the exclusive product. Whereas **40** is produced as a mixture of two isomers, detected by GC/MS analysis. Unfortunately, **40** could not be isolated in pure form, as it was contaminated by **140**, both having almost the same R_f in TLC.

Compound **140** is relatively insoluble in dichloromethane compared to **40** which was made use of to obtain a pure sample of it. Crystallisation by slow diffusion of pentane into a solution of **140** in CH_2Cl_2 yielded plate-shaped crystals of X-ray quality. Compound **140** crystallises in the unit cell $P2_1/c$, monoclinic and is found to have *trans* (*meso*) conformation in the crystal.

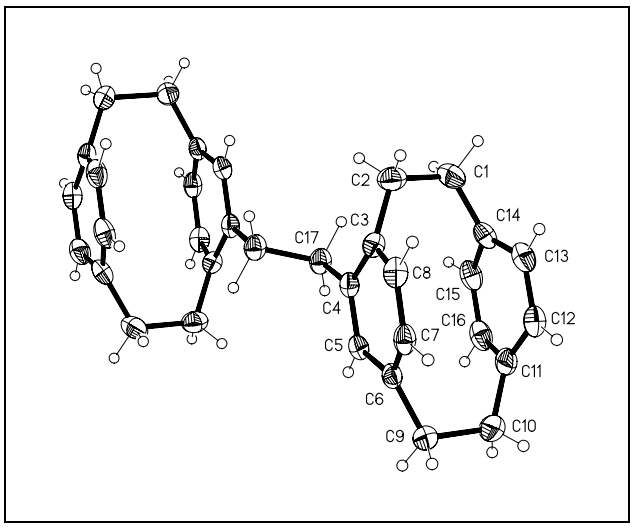
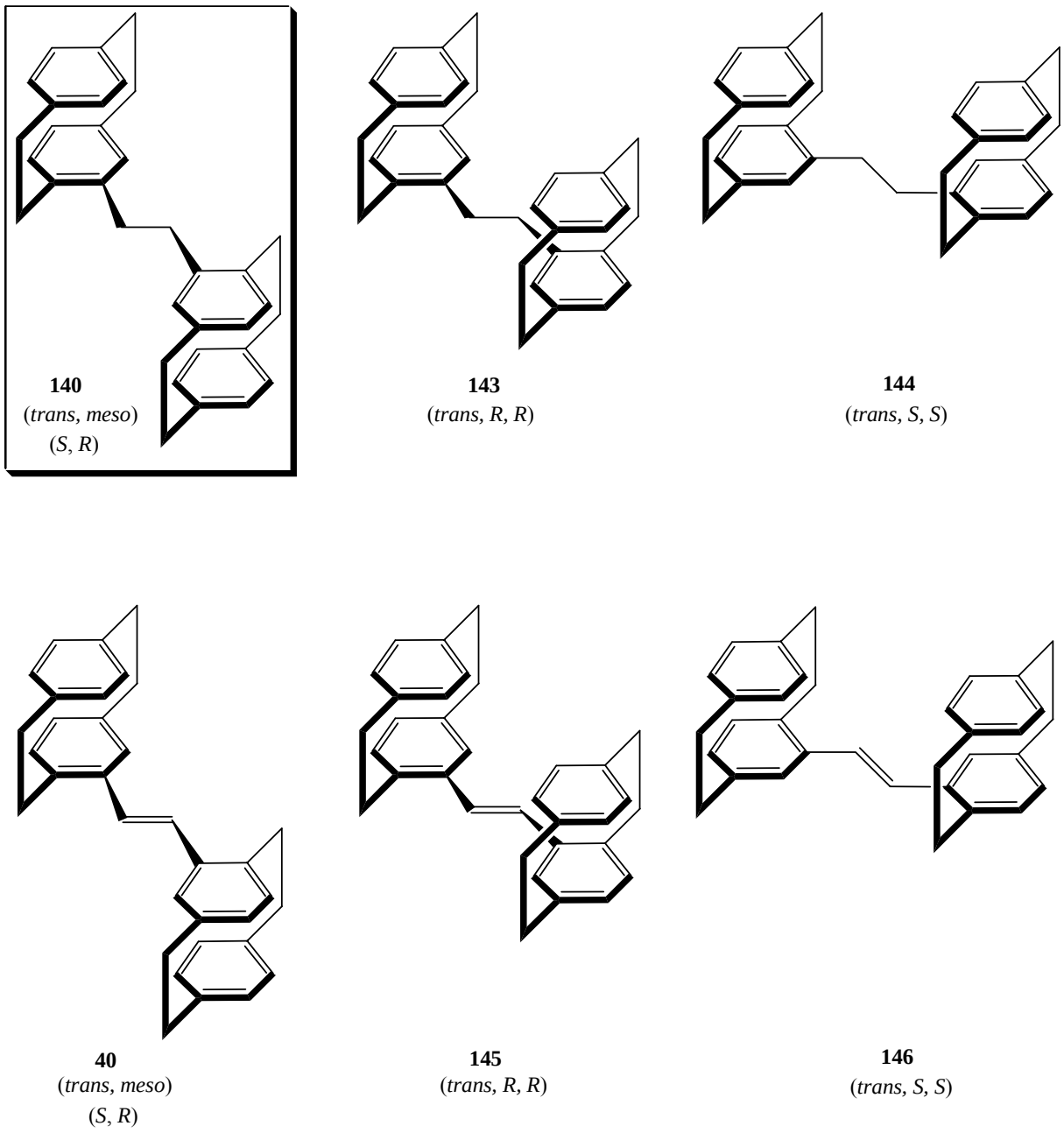


Fig. 19. Structure of 1,2-bis-(4-[2.2]paracyclophanyl)ethane (**140**) in the crystal.



Scheme 78. Possible isomers of **140** and **40** in *trans* conformation.

2.7 Vapour-based polymerisation of functionalised [2.2]paracyclophanes

Generally, CVD polymerisation is a room temperature process, which requires no catalyst, solvent or initiator. Well defined and robust polymer films are produced by this method. In CVD polymerisation (Fig. 20), [2.2]paracyclophane and its derivatives are sublimed under reduced pressure in the sublimation zone that is heated between 220 and 355 °C, depending on the nature of the starting material. The sublimed material is then transferred to the pyrolysis zone where it is exposed to temperatures between 600 and 750 °C using pressures between 0.07 and 0.2 mbar to ensure cleavage of the C-C bonds resulting in the corresponding

para-quinodimethanes (monomers). In the last step, the monomers polymerise on the substrate at a temperature around 25 °C. Utilization of functionalised [2.2]paracyclophanes for CVD polymerisation (Scheme 79) is generally limited by the requirement to preserve the functional groups under the harsh conditions applied in the pyrolysis zone.

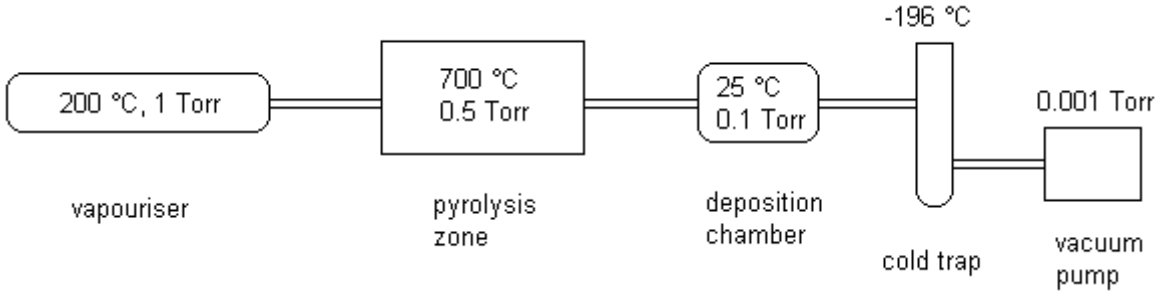
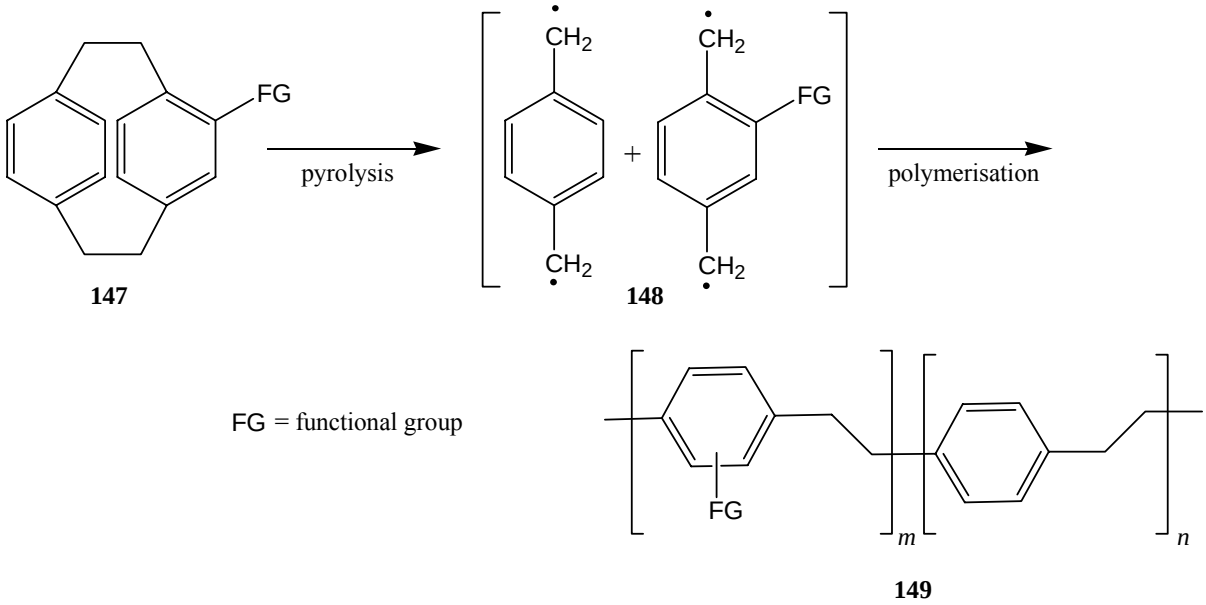


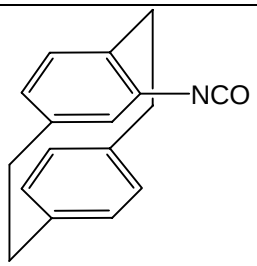
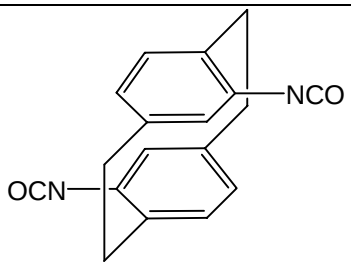
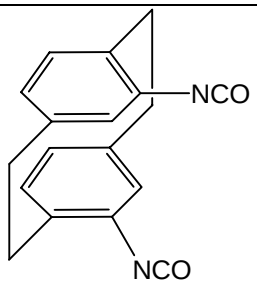
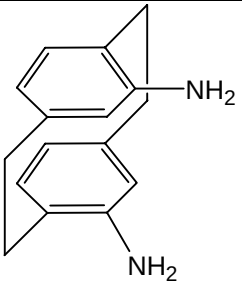
Fig. 20. Schematic representation of CVD apparatus.

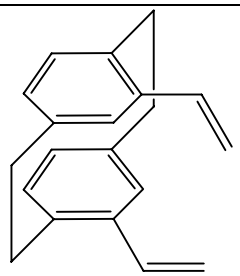
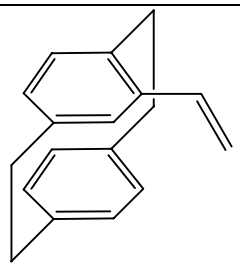
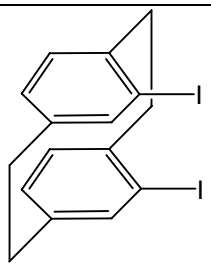
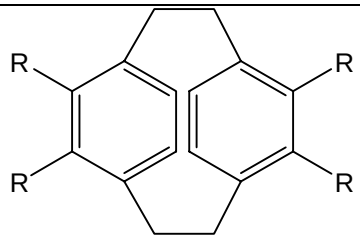
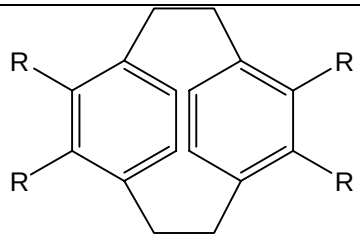


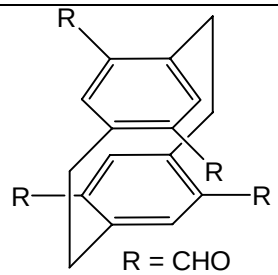
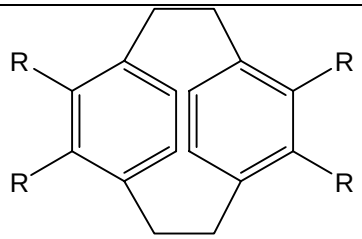
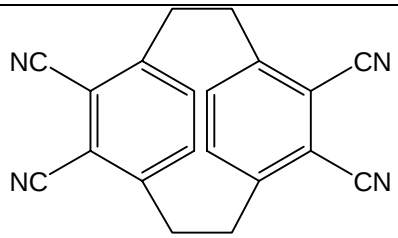
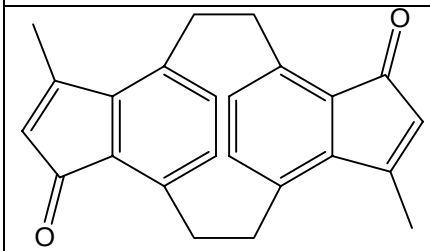
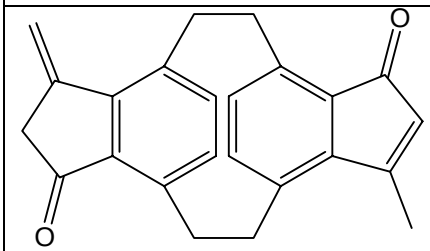
Scheme 79. Mechanism of CVD polymerisation.

[2.2]paracyclophanes bearing isocyanate functional group [**22**, **23** and 4-isocyanato-[2.2]paracyclophane (**150**)] were found to form polymer films with the isocyanate functionality intact, confirmed by the strong absorption band registered at 2271 cm^{-1} in the IR spectrum. *Pseudo-ortho*-diamino[2.2]paracyclophane (**70**) forms polymer film ca. 170 nm in thickness from 20 mg of the substance. In the IR spectrum, the polymer film has very weak or no band corresponding to the amine moiety. Also vinyl[2.2]paracyclophanes **24** and **26** tend to form polymer films with the vinyl moiety intact giving two intensive bands at 2917 and 2849 cm^{-1} in the IR spectrum. The tetraacetyl phane **30** was found to form polymer films but

in trace quantities. Indenonophanes **135** and **136** form coloured and brown polymer films, respectively. In the IR spectrum, **135** exhibits strong band at 1704 cm^{-1} corresponding to α,β-unsaturated ketone. The table below gives an insight to the details of various substances used for CVD polymerisation and the conditions applied for it.

Starting material	T_1 (subl.) /°C	T_2 (pyrol.) /°C	T_3 (pyrol.) /°C	Pressure /mbar	Argon flow /sccm	Result
 **150**	260	750	790	0.20	15	polymerfilm
 **23**	260	750	790	0.20	15	polymerfilm
 **22**	260	750	790	0.20	15	polymerfilm
 **70**	260	750	790	0.20	15	coloured thin polymerfilm

Starting material	T_1 (subl.) /°C	T_2 (pyrol.) /°C	T_3 (pyrol.) /°C	Pressure /mbar	Argon flow /sccm	Result
 **26**	260	750	790	0.20	15	polymerfilm
 **24**	260	750	790	0.20	15	polymerfilm
 **21**	260	750	790	0.20	15	no polymerfilm
 R = CH_2OH **98**	260-300	750	790	0.20	15	trace formation of polymerfilm
	300	600	650	0.07	7	no polymerfilm
 R = $COCH_3$ **30**	260	750	790	0.20	15	trace formation of polymerfilm
	300	600	650	0.07	7	no polymerfilm

Starting material	T_1 (subl.) /°C	T_2 (pyrol.) /°C	T_3 (pyrol.) /°C	Pressure /mbar	Argon flow /sccm	Result
 R = CHO **29**	260	750	790	0.20	15	no polymerfilm
 R = $COOCH_3$ **16**	300	750	790	0.20	15	no polymerfilm
 **96**	300	750	790	0.20	15	no polymerfilm
 **135**	280	720	760	0.20	15	brown polymerfilm
 **136**	280	750	790	0.20	15	coloured polymerfilm

T_1 – sublimation temp. in °C, T_2 and T_3 – pyrolysis temp. in °C, argon flow – standard cubic centimetre-sccm.

Table 5. Summary of CVD polymerisation results.

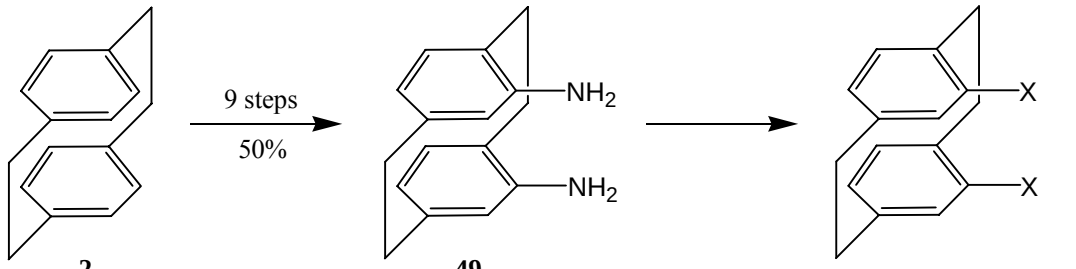
Comparing the entries in Table 5 there is no consistent pattern. It appears that functional groups containing single bond only or possessing relatively mobile X-H bonds are unsuitable

as precursors for polymer films. But it must not be forgotten that film formation depends on many parameters – pyrolysis temperature, speed of moving the reactive *p*-xylylene intermediate through the hot zone (gas flow), the presence of other compounds in the gas phase etc. Since *p*-xylylenes are reactive intermediates it is also conceivable that functional groups could be added to their π-systems thus regenerating aromatic compounds. The production of a Parylene–type polymer is not necessarily the most favoured reaction pathway. That [2.2]paracyclophanes are interesting precursors for advanced materials is illustrated by other recent applications, though.[64]

3. Summary

The aim of this work was to synthesise various functionalised cyclophanes possessing different substitution patterns and to investigate their structural, spectroscopic and chemical properties. These functionalised cyclophanes were also subjected to polymerisation by chemical vapour deposition.

3.1: The first part of this work deals with the syntheses of *pseudo-geminally* substituted dihalo[2.2]paracyclophane derivatives. Functionalisation of the *pseudo-geminal* position was achieved by making use of the intramolecular directing effect of a neighbouring carbonyl group. *Pseudo-geminal*-dichloro (**19**), dibromo (**20**) and diiodo[2.2]paracyclophane (**21**) derivatives have been synthesised successfully in appreciable yields.

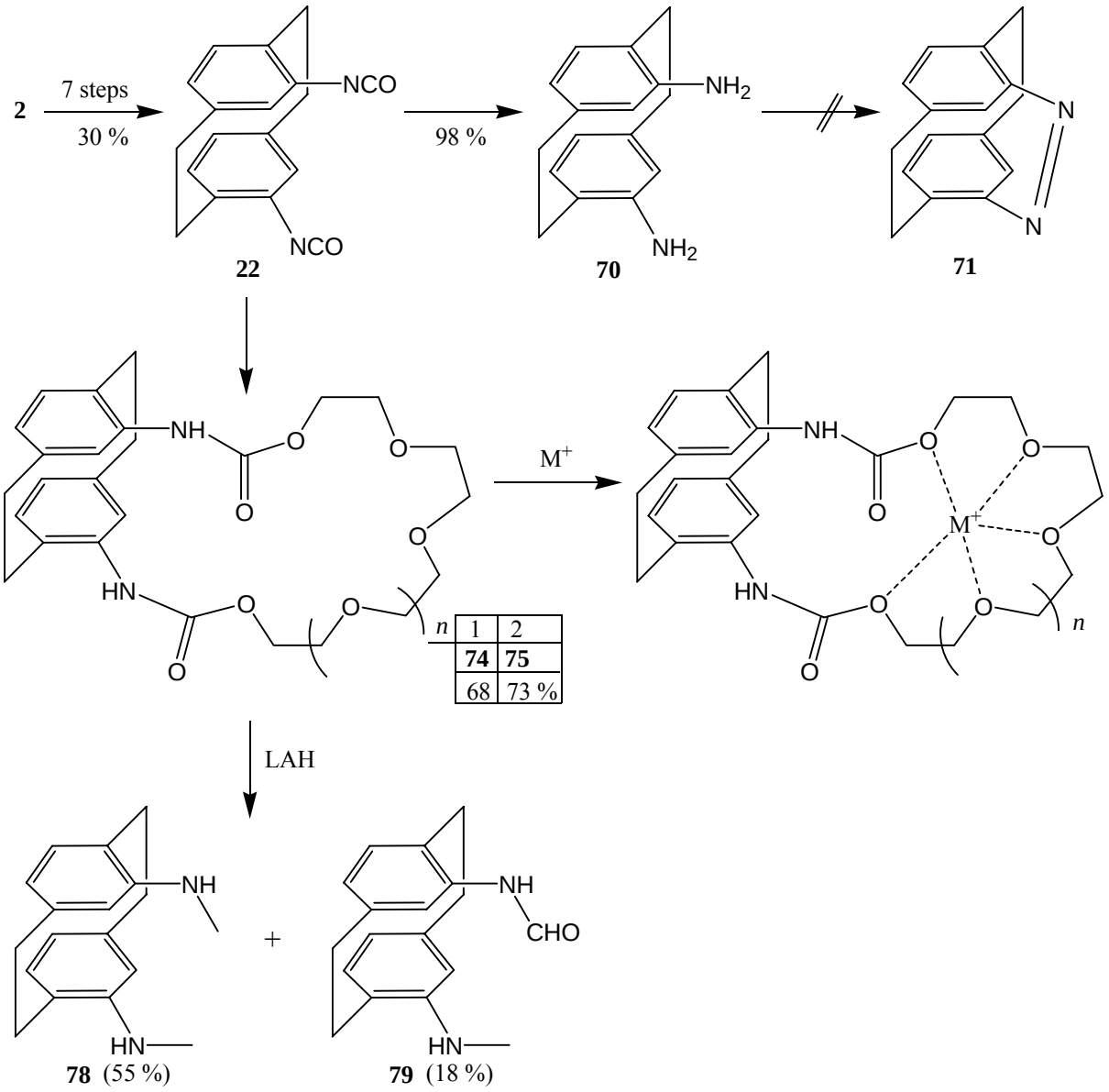


X	F	Cl	Br	I
	18	**19**	**20**	**21**
		35	64	22 %

All derivatives have been characterised fully by spectroscopic methods and their structures were confirmed by single crystal X-ray analysis. The halo derivatives **19**, **20** and **21**, from their crystal structure, display general features of [2.2]paracyclophanes. Two effects of the halogen substituents are: first, the reduced ring angles (C4–C3–C8) at the *ortho* bridgehead carbon atoms to ca. 115° and secondly, the widened C–C–C angles from the substituent to the bridge (e.g., C4–C3–C2) to 123 – 124°, presumably by the steric interactions with the bridge hydrogen atoms. *Pseudo-geminal*-difluoro[2.2]paracyclophane (**18**) was successfully isolated and spectroscopically fully characterised from its mixture of isomers and has been studied thoroughly by NMR spectroscopy.

3.2: The second part of this work involves the successful synthesis of the *pseudo-ortho*-diisocyanato (**22**) and diamino[2.2]paracyclophane (**70**) and its precursors. **22** was synthesised starting from [2.2]paracyclophane in seven steps. Crownophanes **74** and **75** were synthesised

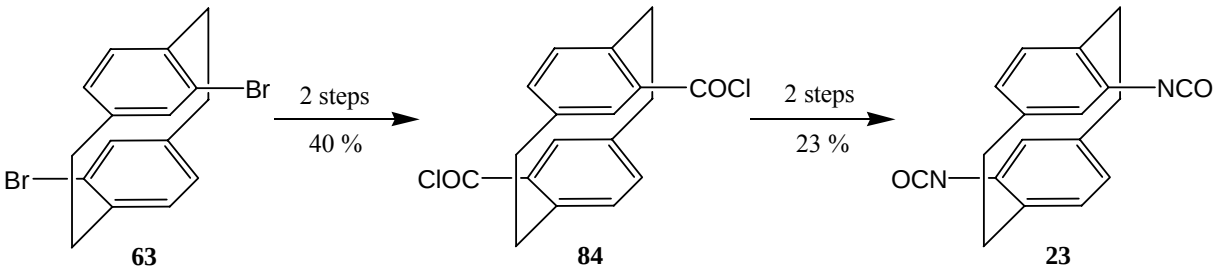
from **22** and their complexation behaviour with alkali metal picrate has been studied. Both crownophanes bind with Na^+ ions more specifically than K^+ and Cs^+ ions.



Attempts to resolve racemic *pseudo-ortho*-diformyl (**66**) and dicarboxy[2.2]paracyclophane (**67**) failed. Compounds **22**, **74** and **75** were, however successfully resolved by chiral HPLC. Density functional theory calculations of **70** revealed that the two amino groups are apart by 4.23 Å, which accounts for the failure of the synthesis of the *pseudo-ortho* bridged azo[2.2]paracyclophane (**71**). Also, the strain energy (rel. SE = 99.8 kcal/mol) of **71** is very high as calculated by using MMX force field programme. Reduction of crownophane **74** using lithium aluminium hydride destroyed the cyclic structure and produced **78** and **79**, respectively, characterised by the conventional spectroscopic methods and single crystal X-ray analysis of **79**. The crownophanes **74**, **75** and *pseudo-ortho*-diisocyanato[2.2]-

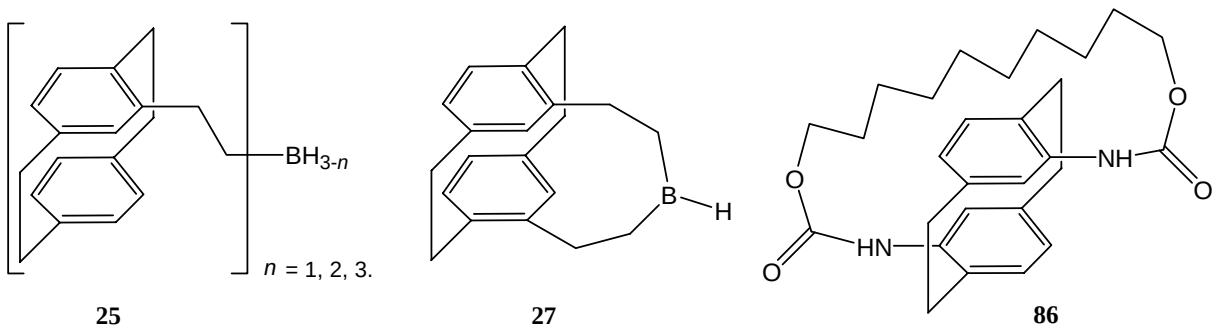
paracyclophane (**22**) were successfully separated by chiral analytical HPLC using cellulose tris(3,5-dimethylphenylcarbamate) (CDMPC).

3.3: The synthetic methodology adopted to synthesise *pseudo-para*-diisocyanato[2.2]-paracyclophane (**23**) was similar to that of the synthesis of **22** and **48**. Surprisingly, the bis(chlorocarbonyl) derivative **84** was found to be quite stable and the structures of both **23** and **84** were confirmed by single crystal X-ray analysis. The conversion of **84** to its corresponding bis(azidocarbonyl) derivative **85** required higher temperatures (50 °C) as to its *pseudo-ortho* or *geminal* isomers.



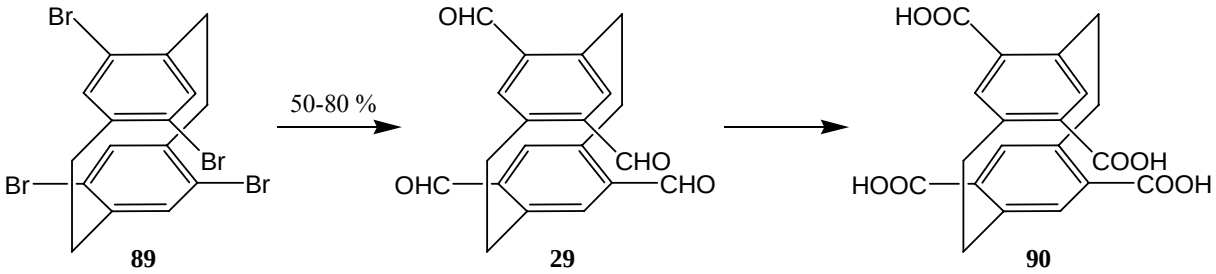
63 **84** **23**

Attempts to synthesise **86** to study the electronic interactions between the aromatic ring and the hydrogen atoms of the bridge were unsuccessful. Attempts to synthesise chiral hydroborating reagents **25** and **27** bearing a [2.2]paracyclophane backbone were also unsuccessful. Borane reagents like BH_3.THF complex and (*S*)-alpine boramine*TMED complex were used for the hydroboration, resulting in a complex mixture of compounds.

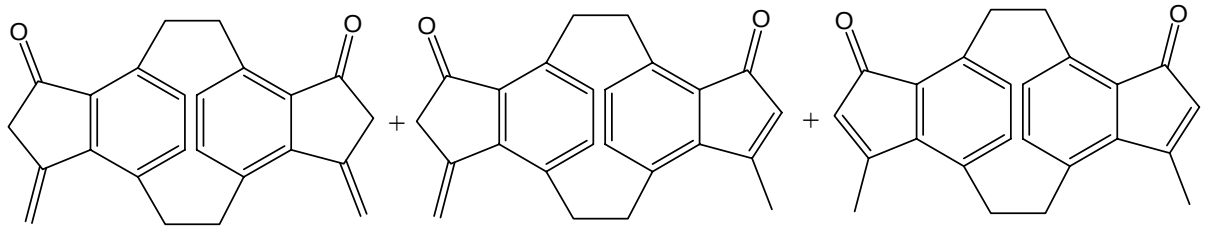


25 **27** **86**

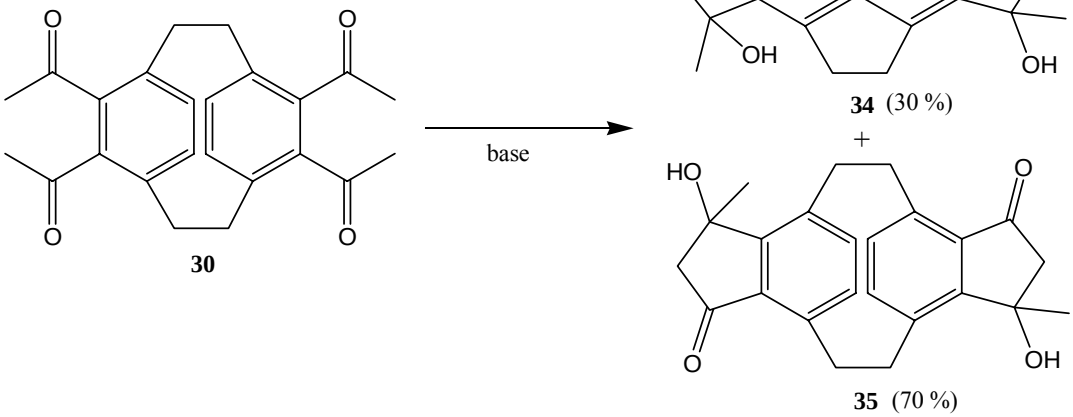
3.4: The fourth part of the thesis deals with the syntheses of multifunctionalised [2.2]paracyclophanes. The syntheses of 4,7,12,15-tetraformyl- (**29**) and tetracarboxy[2.2]paracyclophane (**90**) were accomplished. A drawback of this synthesis was that the reactions could be carried out only on a small scale (100 mg) and the purification of **90** was not possible due to solubility problems.



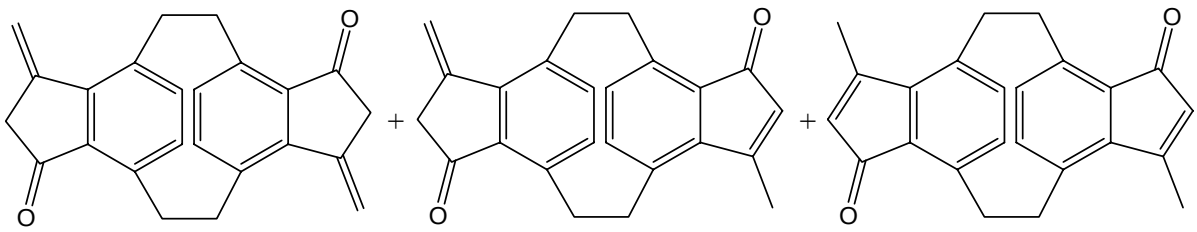
89 **29** **90**



130 (37 %) **129** (30 %) **36** (30 %)



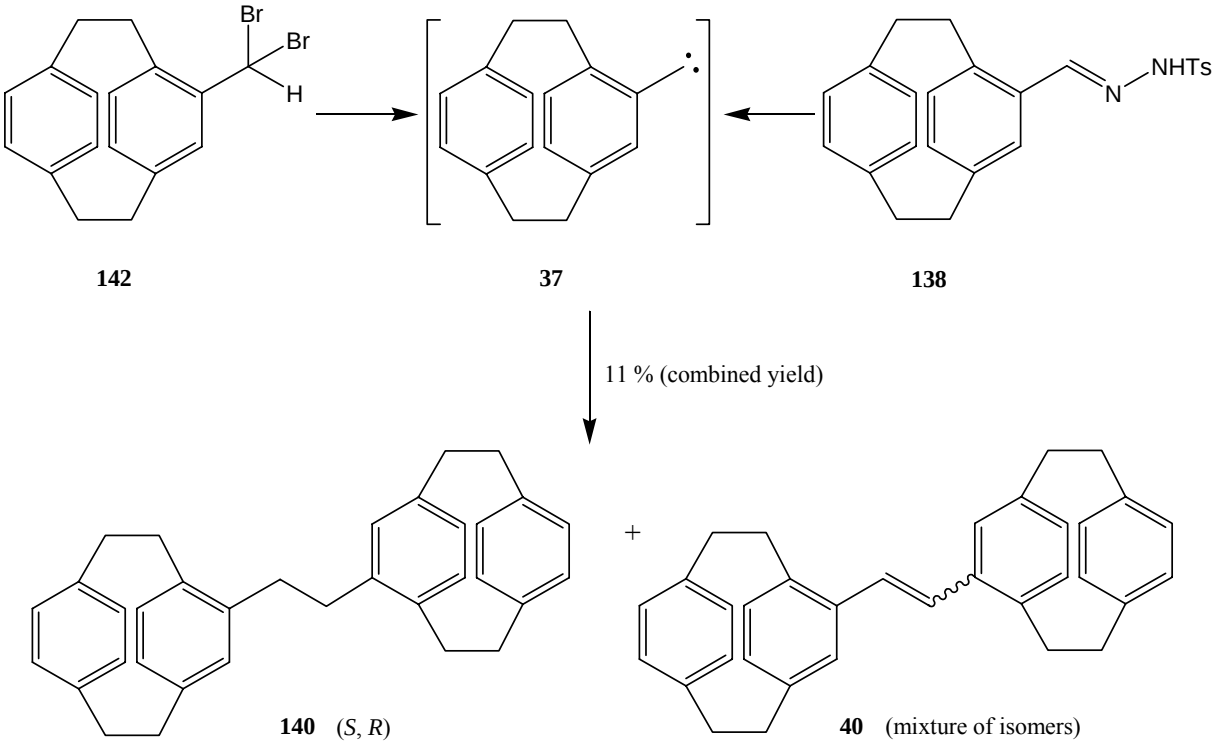
30 **34** (30 %) **35** (70 %)



137 (16 %) **136** (48 %) **135** (16 %)

Several attempts and several synthetic methodologies devised to synthesise 4,5,12,13-tetraformyl[2.2]paracyclophane (**28**) were fruitless. As an alternative compound 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**) was synthesised, although in poor yields (12%). **30** was found to crystallise in two different packing patterns, both possessing inversion symmetry. Base catalysed aldol condensation of **30** produced exclusively indanonophanes **34** and **35** in quantitative yield. Dehydration of **34** and **35** produced six different isomers, which were successfully separated and fully characterised by spectroscopic methods. The α,β-unsaturated indenonophanes **36**, **129**, **135** and **136** are bright yellow coloured compounds having a UV/Vis absorption maximum of 389 nm. Compounds' **34** and **135** structures were confirmed by single crystal X-ray analysis. Gas phase geometrical optimisation using B3LYP/6-31G(d) program of **34** and **35** revealed that the compounds differ from each other by only ± 0.01 kcal/mol.

3.5: 4-Tosylhydrazone[2.2]paracyclophane (**138**) was synthesised from the corresponding formyl derivative **87**, quantitatively. Base-catalysed high temperature reaction of **138** in aprotic solvent (Bamford-Stevens reaction) generated the desired carbene **37**, which underwent dimerisation in an intermolecular fashion to yield compounds **140** and **40**.



As a confirmation that the generated carbene undergoes only intermolecular reaction, the carbene was generated by an alternative route which involves the synthesis of dibromo

compound **142**. This on further treatment with zinc powder yielded **140** and **40**. Compound **140** has the expected *trans* (*S*, *R*) conformation in the crystal, confirmed by X-ray analysis.

3.6: In the last part of this thesis the results of polymerisation studies using chemical vapour deposition of the above synthesised functionalised cyclophanes are discussed. *Pseudo-geminal*-(**48**), *ortho*-(**22**) and *para*-(**23**) diisocyanato[2.2]paracyclophanes were found to polymerise with the functional group intact as confirmed by IR analysis. Also 4-ethenyl-(**24**) and 4,16-diethenyl[2.2]paracyclophane (**26**) polymerised having the unchanged functional group. *Pseudo-ortho*-diamino[2.2]paracyclophane (**70**) forms good polymer film of ca. 170 nm thickness. Indenonophanes **135** and **136** form coloured polymer films with the α,β-unsaturated ketone moiety intact. The other derivatives (**16**, **21**, **29**, **30**, **96** and **98**) did not produce polymer films under the applied reaction conditions.

4 Experimental

4.1 Instrumentation and general experimental considerations

Thin Layer Chromatography (TLC)

Thin layer chromatograms were run on precoated plastic plates, Silica gel (SiO_2): Polygram Sil G/UV_{254} (Macherey-Nagel & Co.) or on Alumina (Al_2O_3): Polygram ALOX N/UV_{254} (Macherey-Nagel & Co.).

Column Chromatography

Column chromatography was performed on Silica gel 60 (70-230 mesh), Merck (Darmstadt). The solvents used for column chromatography were distilled prior to use.

Melting Points

Measurements were made either on a Büchi 510 melting point apparatus or on a MEL-TEMP II (Laboratory Devices, USA) or on a Kofler-Heiztischmikroskop apparatus. The melting points are uncorrected.

Sublimation

A temperature gradient sublimation apparatus from Esoteric Chemicals was used.

NMR Spectroscopy

^1H and ^{13}C spectra were recorded on the following spectrometers: Bruker AC-200: ^1H NMR (200.1 MHz); ^{13}C NMR (50.3 MHz);Bruker DRX-400: ^1H NMR (400.1 MHz); ^{13}C NMR (100.6 MHz). Deuteriochloroform ($CDCl_3$) was used as solvent unless otherwise stated. Chemical shifts are reported in parts per million (δ) downfield from the internal tetramethylsilane reference and the coupling constants are in Hertz. Spin multiplicities are indicated by the following symbols; s (singlet), br. (broad), d (doublet), t (triplet), q (quartet), m (multiplet), qC (quaternary carbon), Ar (aryl). The structures are usually not numbered according to IUPAC rules.

IR Spectroscopy

IR spectra were recorded on a Nicolet 320 FT-IR spectrometer or on a Bruker Tensor 27 spectrometer. Samples were prepared as KBr pellets or as thin films. Band positions are reported in reciprocal centimetres. Band intensities are referred by the following symbols; vs (very strong), s (strong), m (medium), w (weak).

UV/Vis Spectroscopy

UV spectra were recorded on a Varian Cary 100BIO or on a HP 8452 A Diode Array spectrophotometer.

Mass Spectrometry

Mass spectra were recorded on a Finnigan MAT 95 spectrometer using electron ionisation (EI, 70 eV). Electron spray ionisation spectra (ESI) were recorded on a Finnigan MAT 95XLT spectrometer. Spray voltage 1.3-1.8 kV, flow rate 0.5-1.5 μL per min. Methanol was used as solvent unless otherwise specified.

GC/MS

GC/MS traces were recorded on a triple quadrupole mass spectrometer Finnigan TSQ 700 (EI, 70 eV) attached to a Hewlett Packard 5890A gas chromatograph.

Pyrolysis

Pyrolysis was carried on a Gero Standardrohrofen Typ SR (Neuhausen).

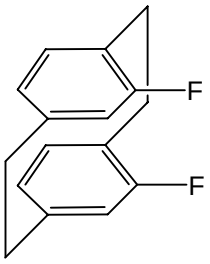
X-ray analysis

X-ray data were obtained on a Bruker SMART 1000 CCD diffractometer. The X-ray data were processed and refined with the SHELXL-97 program.

Nitrogen and argon gas were used for maintaining inert atmosphere. All solvents and chemicals were purified as prescribed in Purification of Laboratory Chemicals, 4^{th} edition, Butterworth-Heinemann, Oxford 2000.

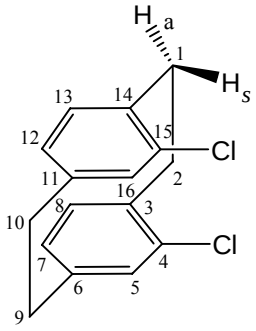
4.2 Experimental procedures

4.2.1: Separation of 4,15-difluoro[2.2]paracyclophane (18)



The mixture of isomers obtained from Dr. K. Ibrom (Braunschweig) of difluoro[2.2]paracyclophane (0.050 g, 0.21 mmol) was subjected to preparative thin layer chromatography (several runs) on silica gel using 1:20 CH_2Cl_2/pentane mixture. The band with the smallest R_f value was scratched out and extracted with CH_2Cl_2. On evaporating the solvent 4,15-difluoro[2.2]paracyclophane (**18**) (< 10 mg) was isolated as a colourless solid. The spectral data agreed with those reported in ref.[11, 17]

4.2.2: 4,15-Dichloro[2.2]paracyclophane (19)



4,15-Diamino[2.2]paracyclophane (**49**) (0.1 g, 0.42 mmol) was dissolved in 10 mL of conc. HCl and the solution cooled to 0 °C with an ice bath under stirring. To this a solution of $NaNO_2$ (0.39 g, 5.65 mmol), dissolved in 5 mL of water and cooled to 0 °C, was added dropwise. The mixture was added to a solution of CuCl (0.8 g, 8.08 mmol) in 5 mL of conc. HCl also at 0 °C. The resulting mixture was allowed to warm to room temperature and stand for 3 h. The reaction mixture was warmed on a water bath kept at 70 °C for 30 min. The mixture was extracted with ether and the ether phase was washed with sat. aq. $NaHCO_3$ solution, brine solution and dried with anhydrous $MgSO_4$. After the solvent had been

evaporated *in vacuo* the crude product was column chromatographed on silica gel with 5% diethyl ether in pentane, thus furnishing 4,15-dichloro[2.2]paracyclophane (**19**) as a colourless solid (40 mg, 0.145 mmol, 35%). Crystallisation using $CHCl_3$/pentane mixture gave colourless tablet-shaped single crystals used for X-ray analysis.

R_f : 0.45 (SiO_2, 1:19 ether/pentane).

m.p.: 186 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.57 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{16\text{-H},12\text{-H}}$ = 1.75 Hz, 5-H, 16-H), 6.53 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.75 Hz, 8-H, 13-H), 6.47 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.76 Hz, $J_{7\text{-H},5\text{-H}} = J_{12\text{-H},16\text{-H}}$ = 1.75 Hz, 7-H, 12-H), 3.76 – 3.71 (m, 2 H, 1*s*-H, 2*s*-H), 3.07 – 2.93 (m, 6 H, 1*a*-H, 2*a*-H, 9-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 140.8 (s, C-6, C-11), 136.6 (s, C-3, C-14), 135.2 (d, C-8, C-13), 134.8 (s, C-4, C-15), 132.9 (d, C-5, C-16), 131.6 (d, C-7, C-12), 34.6 (t, C-9, C-10), 32.2 (t, C-1, C-2).

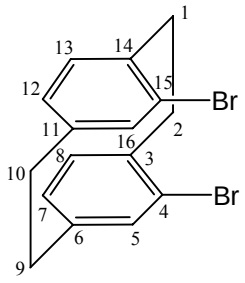
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3444 (m), 3043 (w), 3014 (w), 2963 (w), 2934 (m), 2853 (m), 1587 (m), 1482 (m), 1435 (m), 1395 (s), 1261 (m), 1111 (m), 1043 (s), 838 (m), 708 (s), 698 (m).

UV/Vis ($CHCl_3$): λ_{max} (lg ε) = 328 nm (1.22), 342 (1.18), 358 (1.04, sh).

MS (EI, 70eV): *m*/*z* (%) = 278 (8), 276 (14) [M^+], 202 (2), 172 (3), 140 (30), 138 (100), 103 (22), 77 (14), 63 (4), 51 (8).

HRMS ($C_{16}H_{14}Cl_2$) calc. = 276.047255, found = 276.04729 ± 1 ppm.

4.2.3: 4,15-Dibromo[2.2]paracyclophane (20)



To a solution of 4,15-azo[2.2]paracyclophane (**9**) (0.15 g, 0.64 mmol) in 20 mL of dry CH_2Cl_2, Fe powder (0.15 g, 2.77 mmol) was added, and the reaction mixture was cooled to 0 °C. A solution of Br_2 (0.103 g, 1.28 mmol) in 15 mL of dry CH_2Cl_2 was added dropwise with stirring. The reaction was continued for 30 min at 0 °C. The iron powder was filtered off and the solvent evaporated *in vacuo*. The crude black solid was chromatographed on silica gel

using 5% CH_2Cl_2 in pentane to give 4,15-dibromo[2.2]paracyclophane (**20**) in 64% yield (0.15 g, 0.4 mmol) as a colourless solid. Crystallisation using $CHCl_3$/pentane gave colourless single crystals, irregular-shaped, used for X-ray analysis.

R_f : 0.5 (SiO_2, 1:10 CH_2Cl_2/pentane).

m.p.: 180 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.78 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{16\text{-H},12\text{-H}}$ = 1.37 Hz, 5-H, 16-H), 6.53 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.72 Hz, 8-H, 13-H), 6.50 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.8 Hz, $J_{7\text{-H},5\text{-H}} = J_{12\text{-H},16\text{-H}}$ = 1.5 Hz, 7-H, 12-H), 3.74 – 3.69 (m, 2 H, 1*s*-H, 2*s*-H), 3.05 – 2.95 (m, 6 H, 1*a*-H, 2*a*-H, 9-H, 10-H).

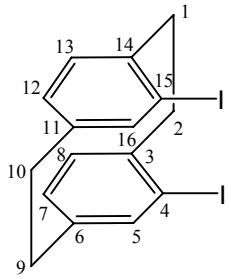
^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 140.8 (s, C-6, C-11), 138.4 (s, C-3, C-14), 135.6 (d, C-5, C-16), 135.0 (d, C-8, C-13), 132.2 (d, C-7, C-12), 125.0 (s, C-4, C-15), 34.6 (t, C-9, C-10), 34.5 (t, C-1, C-2).

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3442 (m), 3068 (w), 3021 (w), 3010 (w), 2958 (w), 2931 (m), 2888 (w), 2851 (w), 1891 (w), 1582 (w), 1537 (w), 1475 (w), 1466 (w), 1449 (w), 1431 (w), 1389 (s), 1189 (w), 1034 (s), 950 (w), 903 (m), 866 (m), 831 (m), 803 (w), 705 (s), 644 (m).

MS (EI, 70eV): *m*/*z* (%) = 368 (18), 366 (30) [M^+], 364 (16), 322 (8), 202 (6), 185 (10), 184 (98), 182 (100), 138 (12), 103 (33), 77 (38) 51 (16), 44 (30).

HRMS ($C_{16}H_{14}Br_2$) calc. = 363.94623, found = 363.94455 ± 4 ppm.

4.2.4: 4,15-Diiodo[2.2]paracyclophane (21)

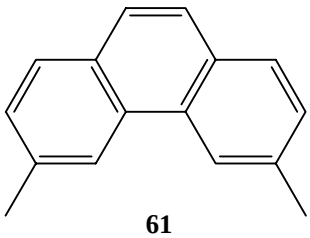


4,15-Azo[2.2]paracyclophane (**9**) (0.2 g, 0.85 mmol) was dissolved in glacial acetic acid (~30 mL) and the mixture was cooled with an ice-water bath under stirring. To this solution ICl (0.153 g, 0.939 mmol) was added, the ice bath was removed, and the stirring was continued at room temp. for 3 h. The crude product was repeatedly extracted in diethyl ether. The combined ether phases were washed with water, sat. aq. $NaHCO_3$ solution, brine solution and dried with anhydrous $MgSO_4$. The solvent was evaporated in a rotary evaporator and the

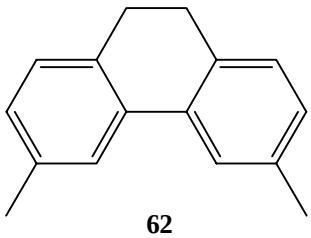
crude was chromatographed on silica gel using 1:5 CH_2Cl_2/pentane as eluent yielding the desired **21** as colourless solid (86 mg, 0.186 mmol, 22%). Colourless prism-shaped single crystals of X-ray quality were obtained by slow diffusion of pentane into a saturated solution of **21** in CH_2Cl_2.

R_f : 0.5 (SiO_2, 1:5 CH_2Cl_2/pentane).
m.p.: 239 °C.
^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.06 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{16\text{-H},12\text{-H}}$ = 1.67 Hz, 5-H, 16-H), 6.54 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.67 Hz, $J_{7\text{-H},5\text{-H}} = J_{12\text{-H},16\text{-H}}$ = 1.66 Hz, 7-H, 12-H), 6.49 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.65 Hz, 8-H, 13-H), 3.62 – 3.57 (m, 2 H, 1*s*-H, 2*s*-H), 3.17 – 3.12 (m, 2 H, 1*a*-H, 2*a*-H), 3.07 – 2.94 (m, 4 H, 9-H, 10-H).
^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 142.4 (s, C-3, C-14), 141.7 (d, C-5, C-16), 140.6 (s, C-6, C-11), 133.8 (d, C-8, C-13), 133.3 (d, C-7, C-12), 99.7 (s, C-4, C-15), 38.8 (t, C-1, C-2), 34.6 (t, C-9, C-10).
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3418 (m), 3029 (m), 2954 (m), 2927 (s), 2886 (m), 2850 (m), 1575 (s), 1532 (s), 1467 (s), 1460 (m), 1446 (s), 1430 (m), 1385 (s), 1024 (vs), 901 (s), 862 (m), 823 (s), 813 (m), 805 (m), 705 (vs), 656 (s), 639 (s), 518 (vs), 454 (m).
UV/Vis (CH_3CN): λ_{max} (lg ε) = 266 nm (3.46), 250 (3.79).
MS (EI, 70eV): *m*/*z* (%) = 460 (16) [M^+], 368 (8), 264 (8), 230 (100), 189 (20), 138 (8), 103 (10), 77 (12), 57 (12).
HRMS ($C_{16}H_{14}I_2$) calc. = 459.9185, found = 459.9178 ± 1 ppm.

4.2.5: Flash Vacuum Pyrolysis of 4,15-azo[2.2]paracyclophane (9)



61



62

In a pyrolysis apparatus consisting of a preheating zone and the actual pyrolysis tube (quartz) 4,15-azo[2.2]paracyclophane (**9**) (0.3 g, 1.28 mmol) was sublimed at 200 °C and 0.01 mbar into the hot zone, which was maintained at 450 °C. Unfortunately, a large fraction of the substrate condensed between the two temperature zones. However, a pyrolysate could be obtained by trapping the pyrolysis vapours in a liquid nitrogen cooled trap. Its TLC

(dichloromethane/pentane, 4:1 v/v) showed that it consisted of two components, 3,6-dimethylphenanthrene (**61**, 4 mg, 1.5%) and 3,6-dimethyl-9,10-dihydrophenanthrene (**62**, 4 mg, 1.5%), both known compounds, the structures of which were determined by NMR and GC/MS analysis.

3,6-dimethylphenanthrene (61): Lit.[56]

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 8.47 (br.s, 2 H), 7.77 (d, 2 H, *J* = 8.1 Hz), 7.41 (br.s, 2 H), 2.63 (s, 6 H, 2 × CH_3).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 135.8, 130.4, 130.0, 128.3, 128.1, 125.7, 122.3, 22.1.

MS (EI, 70eV): *m*/*z* (%) = 206 (100) [M^+], 191 (30), 101 (12), 89 (8), 76 (7).

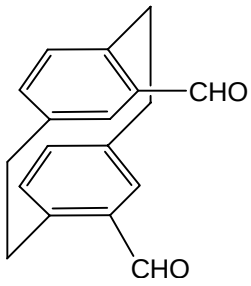
3,6-dimethyl-9,10-dihydrophenanthrene (62): Lit.[57]

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.57 (s, 2 H), 7.12 (d, 2 H, *J* = 7.6 Hz), 7.04 (br.d, 2 H, *J* = 7.6 Hz), 2.81 (s, 4 H, 2 × CH_2), 2.40 (s, 6 H, 2 × CH_3).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 136.2, 134.5, 134.4, 127.9, 124.3, 28.8, 21.4; one signal missing due to signal overlap.

MS (EI, 70eV): *m*/*z* (%) = 208 (98) [M^+], 193 (100), 178 (50), 165 (64), 152 (16), 95 (10), 76 (16).

4.2.6: 4,16-Diformyl[2.2]paracyclophane (66)

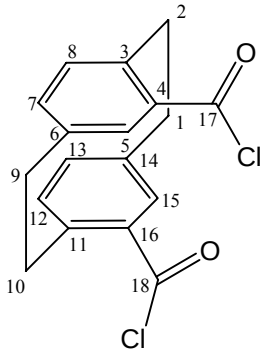


To a stirred solution of 4,16-dibromo[2.2]paracyclophane (**65**, 0.5 g, 1.36 mmol) in 30 mL of anhydrous ether was added at 0 °C 1.87 mL of *n*-BuLi in hexane (1.6 M, 3.01 mmol). The quality of the *n*-BuLi reagent (colourless, clear solution) was found to be important in terms of reaction yields. The reaction mixture (turbid) was allowed to stir at room temperature for 15 min. The reaction mixture was again cooled to 0 °C and *N*-formylpiperidine (0.62 g, 5.46 mmol) was added slowly (solution became clear). Whilst stirring at room temperature for 2 h, the reaction was monitored by TLC. The reaction was quenched by the addition of 3 N aq. HCl solution. The aqueous phase was separated and extracted once with diethyl ether, the

combined organic phases were washed with sat. aq. $NaHCO_3$, brine and dried with anhydrous $MgSO_4$ and the solvent was removed by rotary evaporation. Column chromatographic purification on silica gel using dichloromethane yielded (0.28 g, 1.09 mmol, 82%) of the desired **66** as colourless solid.

The spectral data of **66** agree with the data given in ref.[53]

4.2.7: 4,16-Bis(chlorocarbonyl)[2.2]paracyclophane (68)



(a) To a suspension of 4,16-dicarboxy[2.2]paracyclophane (**67**, 0.800 g, 2.70 mmol) in 8 mL of abs. CH_2Cl_2 was added 8 mL of oxalylchloride and a drop of 10% v/v mixture of dry CH_2Cl_2/DMF at room temperature. The reaction mixture was stirred at room temperature for ca. 3 h till it became clear. Then 10 mL of dry benzene was added and the solvent was evaporated under reduced pressure. The crude (0.899 g, 2.7 mmol, 100% yield) was used for further synthesis.

(b) To a suspension of the 4,16-dicarboxy[2.2]paracyclophane (**67**, 0.16 g, 0.54 mmol) in 7 mL of $SOCl_2$ under N_2 was added 2 drops of DMF and the mixture refluxed for 45 min. The reaction mixture became clear. The solvent was removed under reduced pressure and the crude pale yellow solid (0.175 g, 0.53 mmol, 98%) was dried under high vacuum. The crude was used for further synthesis but resulted in lower yields as compared to that from method (a).

R_f : does not move on TLC (SiO_2).

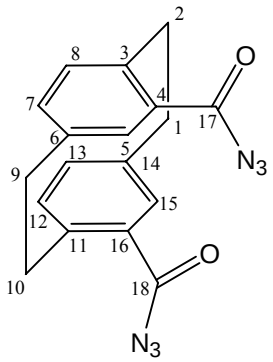
m.p.: 95 °C.

^{1}H NMR (200.1 MHz, $CDCl_3$): δ = 6.95 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.4 Hz, 5-H, 15-H), 6.66 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.5 Hz, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 6.2 Hz, 7-H, 13-H), 6.63 (d, 2 H, $J_{8\text{-}}$

$_{H,7\text{-}H}$ = $J_{12\text{-}H,13\text{-}H}$ = 6.6 Hz, 8-H, 12-H), 3.72 – 3.46 (m, 2 H, bridge-H), 3.30 – 2.97 (m, 4 H, bridge-H).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 139.6, 136.8, 135.9, 134.7, 129.1, 34.2, 33.3; one aromatic carbon atom could not be detected and the carbonyl carbon atom was too weak to be detected.

4.2.8: 4,16-Bis(azidocarbonyl)[2.2]paracyclophane (69)



To a suspension of crude 4,16-bis(chlorocarbonyl)[2.2]paracyclophane (**68**, 0.179 g, 0.54 mmol) in 15 mL of acetone at 0 °C was added dropwise an aqueous solution of NaN_3 (0.35 g, 5.38 mmol) in 10 mL of water, and the mixture stirred at the same temperature for 1 h. Then 50 mL of ice cold water was added and the precipitate was filtered off, the residue washed several times with icecold water and allowed to air dry. The crude pale yellow amorphous solid (0.17 g, 0.49 mmol) was obtained in 90% yield.

R_f : decomposes on TLC (SiO_2).

m.p.: no sharp melting point, as compound gradually decomposes on heating.

^{1}H NMR (200.1 MHz, $CDCl_3$): δ = 7.16 (d, 2 H, $J_{5\text{-}H,7\text{-}H}$ = $J_{15\text{-}H,13\text{-}H}$ = 1.8 Hz, 5-H, 15-H), 6.78 (dd, 2 H, $J_{7\text{-}H,5\text{-}H}$ = $J_{13\text{-}H,15\text{-}H}$ = 1.8 Hz, $J_{7\text{-}H,8\text{-}H}$ = $J_{13\text{-}H,12\text{-}H}$ = 7.9 Hz, 7-H, 13-H), 6.59 (d, 2 H, $J_{8\text{-}H,7\text{-}H}$ = $J_{12\text{-}H,13\text{-}H}$ = 7.9 Hz, 8-H, 12-H), 4.24 – 4.12 (m, 2 H, bridge-H), 3.29 – 3.07 (m, 4 H, bridge-H), 2.93 – 2.78 (m, 2 H, bridge-H).

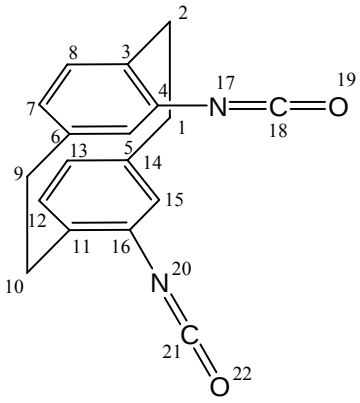
^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 143.4 (s, Ar), 140.6 (s, Ar), 137.7 (d, Ar), 136.4 (d, Ar), 133.5 (d, Ar), 130.0 (s, Ar), 35.7 (t, bridge), 33.9 (t, bridge); due to weak intensity the carbonyl peak was not detected.

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3050 (w), 2968 (w), 2949 (w), 2930 (w), 2855 (w), 2268 (m), 2141 (s), 1680 (s), 1656 (w), 1247 (vs), 1199 (s), 1189 (s), 1155 (m), 1130 (w), 1105 (w), 994 (s), 917 (m), 818 (w), 669 (w).

MS (EI, 70eV): *m*/*z* (%) = 346 (2) [M^+], 318 (1), 290 (20), 266 (2), 145 (100), 116 (9), 90 (15), 63 (5), 51 (5), 44 (9).

HRMS ($C_{18}H_{14}N_6O_2$) not available due to very low intensity of [M^+]

4.2.9: 4,16-Diisocyanato[2.2]paracyclophane (22)



The crude 4,16-bis(azidocarbonyl)[2.2]paracyclophane (**69**, 1.44 g, 4.16 mmol) was taken up in dry toluene (50 mL) under N_2 and the mixture refluxed for 30 min. The solvent was evaporated *in vacuo* and the crude was column chromatographed on silica gel with 1:4 CH_2Cl_2/pentane to yield the *pseudo-ortho*-diisocyanato[2.2]paracyclophane (**22**, 1.2 g, 4.13 mmol, 100%) as colourless solid.

R_f: 0.8 (SiO_2, 1:1 CH_2Cl_2/pentane).

m.p.: 94-96 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.51 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.91 Hz, 8-H, 12-H), 6.49 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.75 Hz, 5-H, 15-H), 6.40 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.75 Hz, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.91 Hz, 7-H, 13-H), 3.34 – 3.27 (m, 2 H, 2-H, 10-H), 3.09 – 2.95 (m, 4 H, 1-H, 9-H), 2.77 – 2.69 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 181.3 (s, C-18, C-21), 141.6 (s, C-6, C-14), 135.1 (d, C-8, C-12), 133.8 (s, C-3, C-11), 133.4 (s, C-4, C-16), 130.3 (d, C-7, C-13), 126.6 (d, C-5, C-15), 33.3 (t, C-1, C-9), 32.2 (t, C-2, C-10).

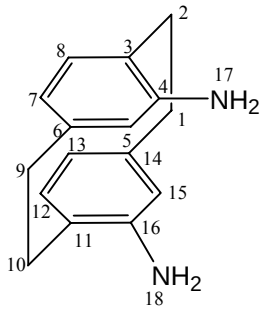
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3047 (w), 2965 (w), 2936 (w), 2855 (w), 2296 (NCO) (vs), 1560 (w), 1505 (w), 1072 (w), 872 (w), 716 (w), 560 (w).

UV/Vis ($CHCl_3$): λ_{max} (lg ε) = 310 nm (2.67), 292 (2.95).

MS (EI, 70eV): *m*/*z* (%) = 290 (24) [M^+], 276 (2), 249 (10), 145 (100), 138 (20), 116 (9), 104 (28), 90 (12), 63 (5), 51 (5).

HRMS ($C_{18}H_{14}N_2O_2$) calc. = 290.105527, found = 290.10542 ± 1 ppm.

4.2.10: 4,16-Diamino[2.2]paracyclophane (70)



4,16-Diisocyanato[2.2]paracyclophane (**22**, 0.100 g, 0.345 mmol) was taken up in 10 mL of ethanol and the mixture was refluxed for 2 h. To this solution was added 5 mL of 20% aq. KOH solution and the mixture refluxed for 45 h with stirring. To the cooled reaction mixture was added 30 mL of 20% aq. KOH solution and the mixture stirred for 5 min. The precipitate was filtered off, washed several times with water and dried yielding the *pseudo-ortho*-diamino[2.2]paracyclophane (**70**, 0.08 g, 0.336 mmol, 98%) as a pale brown solid.

R_f : 0.42 (SiO_2, EtOAc).

m.p.: >200 °C (decomp.)

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.28 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.69 Hz, 8-H, 12-H), 6.11 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.57 Hz, 5-H, 15-H), 5.96 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.69 Hz, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.63 Hz, 7-H, 13-H), 3.32 (br.s, 4 H, 17-H, 18-H), 2.99 – 2.93 (m, 2 H, 2-H, 10-H), 2.88 – 2.78 (m, 4 H, 1-H, 9-H), 2.58 – 2.50 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 144.5 (s, C-4, C-16), 141.1 (s, C-6, C-14), 135.1 (d, C-8, C-12), 124.1 (s, C-3, C-11), 123.1 (d, C-7, C-13), 116.3 (d, C-5, C15), 32.7 (t, C-1, C-9), 32.0 (t, C-2, C-10).

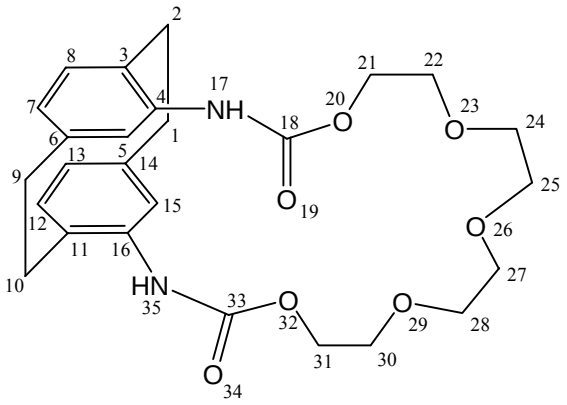
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3368 (w), 2923 (w), 2896 (w), 2852 (w), 1608 (m), 1563 (w), 1496 (w), 1422 (w), 1282 (w), 981 (w), 859 (w), 784 (w), 715 (w), 664 (w), 540 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 321 nm (3.08), 274 (3.50).

MS (EI, 70eV): *m*/*z* (%) = 238 (36) [M^+], 119 (100), 91 (12), 44 (4).

HRMS ($C_{16}H_{18}N_2$) calc. = 238.14699, found = 238.14702 ± 1.5 ppm.

4.2.11: *Pseudo-ortho*-crownophane (74)



Pseudo-ortho-diisocyanato[2.2]paracyclophane (**22**, 0.07 g, 0.24 mmol) was taken up in 100 mL of anhydrous toluene under N_2 with stirring. The reaction mixture was set to reflux and a solution of tetraethyleneglycol (0.046 g, 0.24 mmol) taken up in 50 mL of anhydrous toluene was added slowly at a rate of 1.2 mL/h. The reaction mixture was refluxed under stirring for 7 d. The solvent was evaporated under vacuum and the crude product was subjected to column chromatography on silica gel with 3:7 hexane/EtOAc, yielding (0.08 g, 0.165 mmol, 68%) of crownophane (**74**) as colourless solid. Plate-like single crystals for X-ray analysis were obtained by slow diffusion of pentane into the solution of **74** in CH_2Cl_2.

R_f: 0.35 (SiO_2, EtOAc).

m.p.: 176 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.3 (br.s, 2 H, NH, 17-H, 35-H), 6.73 (d, 2 H, $J_{5\text{-H},7\text{-H}}$ = $J_{15\text{-H},13\text{-H}}$ = 1.23 Hz, 5-H, 15-H), 6.51 (d, 2 H, $J_{8\text{-H},7\text{-H}}$ = $J_{12\text{-H},13\text{-H}}$ = 7.84 Hz, 8-H, 12-H), 6.38 (dd, 2 H, $J_{7\text{-H},5\text{-H}}$ = $J_{13\text{-H},15\text{-H}}$ = 1.64 Hz, $J_{7\text{-H},8\text{-H}}$ = $J_{13\text{-H},12\text{-H}}$ = 7.83 Hz, 7-H, 13-H), 4.63 (br., 2 H, 21-H, 31-H), 4.16 (br., 2 H, 21-H, 31-H), 3.82 – 3.62 (m, 12 H, 22-H, 24-H, 25-H, 27-H, 28-H, 30-H,), 3.30 – 3.24 (m, 2 H, 2-H, 10-H), 3.06 – 2.91 (m, 4 H, 1-H, 9-H), 2.79 – 2.72 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 154.3 (s, C-18, C-33), 140.7 (s, C-4, C-16), 136.1 (s, C-6, C-14), 135.3 (d, C-8, C-12), 132.1 (s, C-3, C-11), 129.6 (d, C-7, C-13), 123.1 (d, C-5, C-15), 70.7, 70.5, 69.5, 63.9 (t, C-21, C-22, C-24, C-25, C-27, C-28, C-30, C-31), 33.3 (t, C-1, C-9), 32.6 (t, C-2, C-10).

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3256 (w), 3039 (w), 2981 (w), 2956 (w), 2946 (w), 2925 (w), 2893 (w), 2858 (w), 1738 (vs), 1719 (s), 1708 (w), 1687 (vs), 1603 (w), 1548 (m), 1531 (m), 1496 (w), 1267 (w), 1245 (s), 1231 (s), 1131 (w), 1103 (m), 1087 (w), 1073 (w).

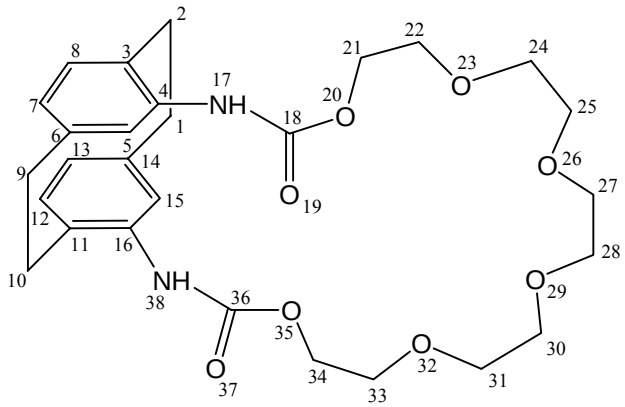
UV/Vis ($CHCl_3$): λ_{max} (lg ε) = 314 nm (2.54), 300 (2.75), 290 (3.03), 268 (3.45);

(CH_2Cl_2): λ_{max} (lg ε) = 314 nm (2.62), 300 (2.75), 290 (3.03), 268 (3.61).

MS (EI, 70eV): *m*/*z* (%) = 484 (32) [M^+], 396 (6), 352 (4), 308 (2), 290 (28), 279 (6), 190 (20), 167 (11), 149 (20), 145 (100), 119 (10), 89 (13), 71 (10), 57 (15), 45 (19).

HRMS ($C_{26}H_{32}N_2O_7$) calc. = 484.220951, found = 484.22096 ± 1 ppm.

4.2.12: *Pseudo-ortho*-crownophane (75)



Pseudo-ortho-diisocyanato[2.2]paracyclophane (**22**, 0.07 g, 0.24 mmol) was taken up in 100 mL of anhydrous toluene under N_2 with stirring. The reaction mixture was set to reflux and a solution of pentaethyleneglycol (0.057 g, 0.24 mmol) taken up in 50 mL of anhydrous toluene was added slowly at a rate of 1.2 mL/h. After refluxing with stirring for 7 d the solvent was evaporated *in vacuo* and the crude product was subjected to column chromatography on neutral alumina with 1:1 hexane/EtOAc; yielding 0.09 g of crownophane (**75**, 0.17 mmol, 73%) as colourless solid.

R_f : 0.2 (SiO_2, EtOAc), 0.6 (Al_2O_3, EtOAc).

m.p.: 147 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.35 (br.s, 2 H, NH, 17-H, 38-H), 6.70 (br., 2 H, 5-H, 15-H), 6.51 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.84 Hz, 8-H, 12-H), 6.38 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.43 Hz, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.83 Hz, 7-H, 13-H), 4.53 (br., 2 H, 21-H, 34-H), 4.26 (br., 2 H, 21-H, 34-H), 3.84 – 3.64 (m, 16 H, 22-H, 24-H, 25-H, 27-H, 28-H, 30-H, 31-H, 33-H), 3.33 – 3.27 (m, 2 H, 2-H, 10-H), 3.07 – 2.90 (m, 4 H, 1-H, 9-H), 2.78 – 2.08 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 154.2 (s, C-18, C-36), 140.7 (s, C-4, C-16), 136.02 (s, C-6, C-14), 135.5 (d, C-8, C-12), 132.2 (s, C-3, C-11), 129.7 (d, C-7, C-13), 123.2 (d, C-5, C-

15), 70.89, 70.82, 70.76, 69.5 (t, C-22, C-24, C-25, C-27, C-28, C-30, C-31, C-33), 64.4 (t, C-21, C-34), 33.2 (t, C-1, C-9), 32.9 (t, C-2, C-10).

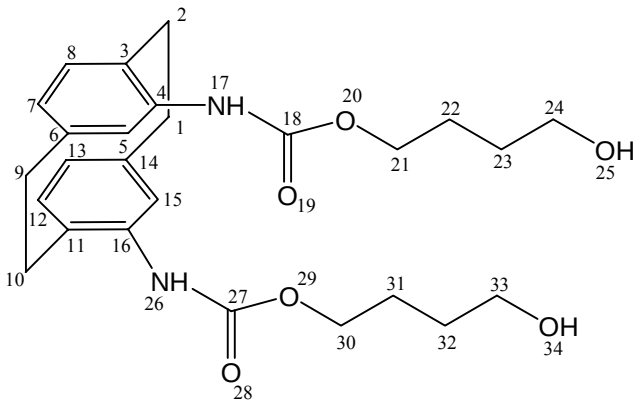
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3436 (w), 3330 (s), 3312 (s), 3014 (w), 2947 (s), 2927 (s), 2881 (s), 2866 (s), 2811 (w), 1727 (vs), 1704 (vs), 1599 (s), 1574 (s), 1533 (vs), 1519 (vs), 1493 (vs), 1454 (s), 1435 (s), 1422 (m), 1358 (w), 1294 (s), 1245 (vs), 1229 (vs), 1223 (vs), 1199 (m), 1130 (s), 1102 (vs), 1073 (vs), 1044 (m), 1032 (m), 963 (w), 879 (m), 712 (w), 664 (m), 637 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 268 nm (3.72), 236 (4.12).

MS (EI, 70eV): *m*/*z* (%) = 528 (41) [M^+], 484 (5), 440 (6), 396 (5), 352 (6), 308 (5), 290 (26), 190 (41), 145 (100), 119 (16), 89 (26), 55 (11).

HRMS ($C_{28}H_{36}N_2O_8$) calc. = 528.247166, found = 528.24515 ± 1 ppm.

4.2.13: 4,16-Dicarbamicacid(4-hydroxybutyl)ester[2.2]paracyclophane (76)



A dried, N_2 flushed three-necked flask with reflux condenser and a dropping funnel was charged with 1,4-butanediol (0.124 g, 1.37 mmol) along with 50 mL of anhydrous toluene. The stirred reaction mixture was refluxed, and 4,16-diisocyanato[2.2]paracyclophane (**22**, 0.100 g, 0.35 mmol) in 15 mL of toluene was added slowly. The reaction mixture was refluxed for 20 h, cooled, and the solvent was evaporated *in vacuo*. The crude product was column chromatographed on silica gel with ethyl acetate yielding the desired 4,16-dicarbamicacid(4-hydroxybutyl)ester[2.2]paracyclophane (**76**, 0.07 g, 0.15 mmol) in 43% as a colourless solid.

R_f : 0.25 (SiO_2, EtOAc).

m.p.: 60 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.31 (br.s, 2 H, NH, 17-H, 26-H), 6.69 (br., 2 H, 5-H, 15-H), 6.50 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.84 Hz, 8-H, 13-H), 6.38 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.35 Hz, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.83 Hz, 7-H, 13-H), 4.29 – 4.20 (m, 4 H, 21-H, 30-H), 3.71 – 3.65 (m, 4 H, 24-H, 33-H), 3.32 – 3.26 (m, 2 H, 2-H, 10-H), 3.08 – 3.03 (m, 2 H, 1-H, 9-H), 2.96 – 2.88 (m, 2 H, 1-H, 9-H), 2.77 – 2.69 (m, 2 H, 2-H, 10-H), 2.17 (br.s, 2 H, OH, 25-H, 34-H), 1.82 – 1.65 (m, 8 H, 22-H, 23-H, 31-H, 32-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 154.6 (s, C-18, C-27), 140.6 (s, Ar), 136.1 (s, Ar), 135.5 (d, C-8, C-12), 129.5 (d, C-7, C-13), 123.0 (d, C-5, C-15), 65.2 (t, C-21, C-30), 62.2 (t, C-24, C-33), 33.2 (t, C-1, C-9), 32.9 (t, C-2, C-10), 29.1 (t, C-23, C-32), 25.5 (t, C-22, C-31); one carbon atom not solved due to extended line broadening.

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3313 (s), 3301 (s), 3050 (w), 3013 (w), 2944 (s), 2869 (m), 1704 (vs), 1599 (s), 1572 (s), 1529 (vs), 1494 (vs), 1457 (s), 1439 (m), 1422 (s), 1407 (m), 1389 (w), 1321 (w), 1292 (s), 1232 (vs), 1199 (w), 1158 (w), 1102 (w), 1060 (s), 953 (w), 880 (w), 774 (w), 735 (s), 715 (w), 662 (m), 649 (m).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 268 nm (3.68), 234 (4.14).

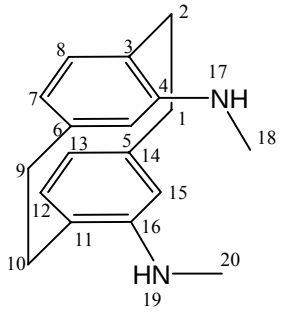
MS (EI, 70eV): *m*/*z* (%) = 470 (12) [M^+], 398 (1), 380 (12), 354 (19), 308 (24), 290 (19), 264 (12), 238 (10), 163 (29), 146 (86), 145 (100), 119 (48), 91 (13), 55 (13), 42 (14).

HRMS ($C_{26}H_{34}N_2O_6$) calc. = 470.241687, found = 470.24153 ± 2 ppm.

4.2.14: Reduction of 74 with lithium aluminium hydride

A dried, N_2 flushed, 100 mL two-necked flask with reflux condenser and stirrer, was charged with crownophane (**74**, 0.100 g, 0.21 mmol) along with 50 mL of anhydrous THF. To this solution $LiAlH_4$ (0.039 g, 1.03 mmol) was added with stirring (note: highly exothermic). The reaction mixture was refluxed for 7 h, avoiding light exposure, and then cooled to room temperature, and finally quenched by adding water. THF was evaporated in a rotary evaporator, and the water phase was extracted with CH_2Cl_2. The organic phase was washed with aq. sat. $NaHCO_3$, brine, dried with anhydrous $MgSO_4$ and solvent evaporated *in vacuo*. The crude product was subjected to flash column chromatography on silica gel with 7:3 EtOAc/hexane yielding (**78**, 0.03 g, 0.113 mmol) as colourless solid in 55% and (**79**, 0.01 g, 0.036 mmol) also as colourless solid in 18%, respectively. Compound **79** was recrystallised from CH_2Cl_2/pentane to give tablet-shaped single crystals. During the whole reaction and workup procedure exposure to light was avoided. The compounds were characterised immediately as with exposure to light and with time they decomposed readily.

***pseudo-ortho*-(*N*-methyl)(*N'*-methyl)diamino[2.2]paracyclophane (78)**



R_f : 0.72 (SiO_2, 7:3 EtOAc/hexane).

m.p.: 175-177 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.26 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{12\text{-H},13\text{-H}}$ = 7.49 Hz, 8-H, 12-H), 5.91 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{13\text{-H},12\text{-H}}$ = 7.54 Hz, $J_{7\text{-H},5\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.66 Hz, 7-H, 13-H), 5.88 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.51 Hz, 5-H, 15-H), 3.43 (br.s, 2 H, 17-H, 19-H), 2.98 – 2.82 (m, 6 H, 1-H, 2-H, 9-H, 10-H), 2.66 (s, 6 H, 18-H, 20-H), 2.59 – 2.52 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 147.7 (s, C-4, C-16), 141.4 (s, C-6, C-14), 134.6 (d, C-8, C-12), 123.3 (s, C-3, C-11), 121.1 (d, C-7, C-13), 111.7 (d, C-5, C-15), 33.1 (t, C-1, C-9), 32.4 (t, C-2, C-10), 30.5 (q, C-18, C-20).

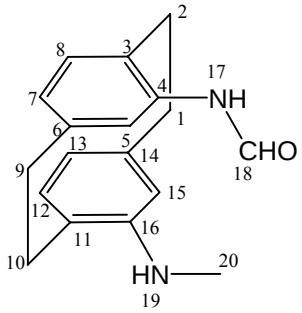
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3370 (w), 2922 (m), 2854 (m), 1593 (s), 1567 (s), 1505 (s), 1443 (s), 1407 (s), 1259 (w), 1148 (w), 1118 (w), 1055 (w), 846 (w), 779 (w), 761 (w), 666 (s), 544 (s).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 306 nm (3.44), 278 (3.75).

MS (EI, 70eV): *m*/*z* (%) = 266 (25) [M^+], 133 (100), 125 (12), 111 (24), 97 (31), 83 (30), 69 (40), 57 (52), 44 (8).

HRMS ($C_{18}H_{22}N_2$) calc. = 266.17829, found = 266.17835 ± 1 ppm.

***pseudo-ortho*-(*N*-formyl)(*N'*-methyl)diamino[2.2]paracyclophane (79)**



Assignment of peaks not experimentally proved. The interpretation rest on comparison with compound **78**.

R_f : 0.47 (SiO_2, 7:3 EtOAc/hexane).

m.p.: 194 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 8.37 (d, 1 H, $J_{18\text{-H},17\text{-H}}$ = 11.47 Hz, 18-H), 7.24 (br.s, 1 H, 17-H), 6.58 (d, 1 H, $J_{5\text{-H},7\text{-H}}$ = 1.40 Hz, 5-H), 6.51 (d, 1 H, $J_{8\text{-H},7\text{-H}}$ = 7.83 Hz, 8-H), 6.31 (dd, 1 H, $J_{7\text{-H},8\text{-H}}$ = 7.83 Hz, $J_{7\text{-H},5\text{-H}}$ = 1.57 Hz, 7-H), 6.27 (d, 1 H, $J_{12\text{-H},13\text{-H}}$ = 7.65 Hz, 12-H), 5.99 (dd, 1 H, $J_{13\text{-H},12\text{-H}}$ = 7.63 Hz, $J_{13\text{-H},15\text{-H}}$ = 1.61 Hz, 13-H), 5.68 (d, 1 H, $J_{15\text{-H},13\text{-H}}$ = 1.54 Hz, 15-H), 3.40 (br.s, 1 H, 19-H), 3.17 – 2.51 (m, 8 H, 1-H, 2-H, 9-H, 10-H), 2.68 (s, 3 H, 20-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 163.2 (d, C-18), 147.9 (s, C-14/16), 141.5 (s, C-4/6), 141.3 (s, C-14/16), 135.5 (d, C-8), 135.2 (d, C-12), 134.8 (s, C-4/6), 130.1 (d, C-7), 129.1 (s, C-3), 123.9 (s, C-11), 121.3 (d, C-13), 119.5 (d, C-5), 112.1 (d, C-15), 33.7 (t, C-1), 33.1 (t, C-9), 32.1 (t, C-10), 31.9 (t, C-2), 30.9 (q, C-20).

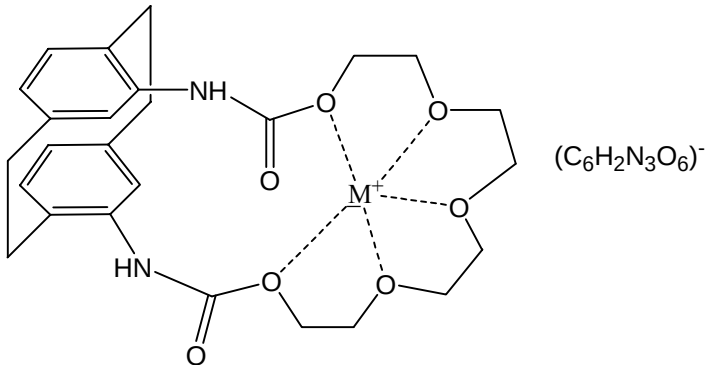
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3412 (w), 3231 (w), 2891 (w), 2852 (w), 1662 (m), 1634 (m), 1593 (w), 1565 (m), 1514 (s), 1410 (w), 1381 (w), 1249 (w), 1153 (w), 1060 (w), 889 (w), 863 (w), 714 (m), 665 (m), 552 (m).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 278 nm (3.72).

MS (EI, 70eV): *m*/*z* (%) = 280 (24) [M^+], 133 (100), 104 (15), 91 (12), 78 (12), 44 (5).

HRMS ($C_{18}H_{20}N_2O$) calc. = 280.15756, found = 280.15641 ± 1 ppm.

4.2.15: Alkali metal complex of 74



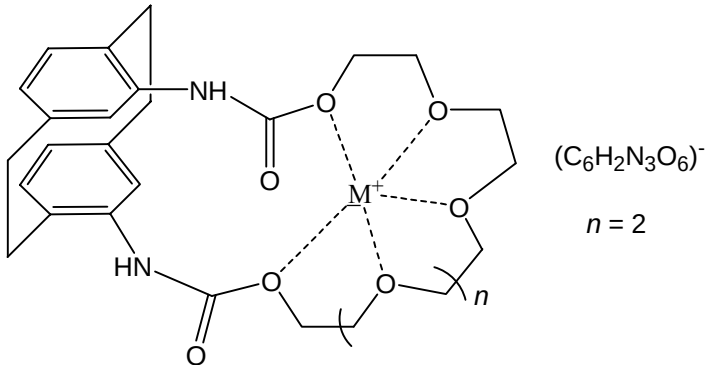
10 mg (0.02 mmol) of racemic crownophane (**74**) was dissolved in 0.6 mL of $CDCl_3$ and the solution placed in a NMR tube. A solution of alkali metal picrate[58] (1 equivalent), dissolved in D_2O, was added, and the two components mixed well during a period of 5 min. The phases were allowed to separate and then the NMR measurements were performed. The organic phase was separated and the solvent was evaporated and dried under high vacuum. The products were characterised my mass spectrometry.

Sodium complex: **MS** (ESI, +ve): 507 (100%) ($C_{26}H_{32}N_2O_7Na^+$).

Potassium complex: **MS** (ESI, +ve): 523 (< 2%) ($C_{26}H_{32}N_2O_7K^+$).

Cesium complex: **MS** (ESI, +ve): 617 (< 2%) ($C_{26}H_{32}N_2O_7Cs^+$).

4.2.16: Alkali metal complex of 75



In a NMR tube (10 mg, 0.019 mmol) of racemic crownophane (**75**) was dissolved in 0.6 mL of $CDCl_3$. A solution of alkali metal picrate[58] (1 equivalent), dissolved in D_2O, was added, and the two components were mixed well during 5 min. The phases were allowed to separate and then the NMR measurements were performed. The organic phase was separated and the

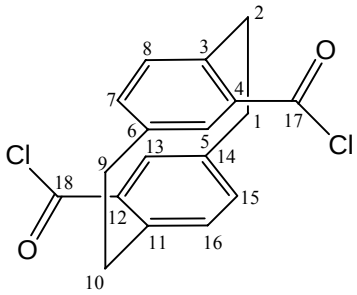
solvent was evaporated and dried under high vacuum. The products were characterised my mass spectrometry.

Sodium complex: **MS** (ESI, +ve): 551 (100%) ($C_{28}H_{36}N_2O_8Na^+$).

Potassium complex: **MS** (ESI, +ve): 567 (14%) ($C_{28}H_{36}N_2O_8K^+$).

Cesium complex: **MS** (ESI, +ve): 661 (2%) ($C_{28}H_{36}N_2O_8Cs^+$).

4.2.17: 4,12-Bis(chlorocarbonyl)[2.2]paracyclophane (84)



To a suspension of 4,12-dicarboxy[2.2]paracyclophane (**83**, 0.4 g, 1.35 mmol) in 5 mL of $SOCl_2$ under N_2 was added a drop of DMF and the mixture refluxed till the solution became clear. The solvent was removed under high vacuum to yield (0.45 g, 1.35 mmol) *pseudo-para*-bis(chlorocarbonyl)[2.2]paracyclophane (**84**) quantitatively as pale yellow solid. Recrystallisation from CH_2Cl_2/pentane by slow diffusion method yielded tablet-shaped single crystals used for X-ray analysis.

R_f : does not move on TLC (hydrolysis).

m.p.: 210 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 7.40 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.83 Hz, 5-H, 13-H), 6.87 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.91 Hz, $J_{7\text{-H},8\text{-H}} = J_{15\text{-H},16\text{-H}}$ = 7.82 Hz, 7-H, 15-H), 6.58 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{16\text{-H},15\text{-H}}$ = 7.84 Hz, 8-H, 16-H), 3.93 – 3.86 (m, 2 H, 2-H, 10-H), 3.27 – 3.23 (m, 4 H, 1-H, 9-H), 3.03 – 2.96 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 167.4 (s, C-17, C-18), 143.7 (s, C-3, C-11), 140.9 (s, C-4, C-12), 137.9 (d, C-5, C-13), 136.7 (d, C-7, C-15), 135.4 (d, C-8, C-16), 134.0 (s, C-6, C-14), 34.9 (t, C-2, C-10), 33.8 (t, C-1, C-9).

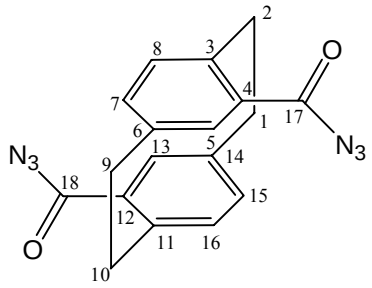
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3017 (w), 2949 (w), 2940 (w), 2924 (w), 2853 (w), 2563 (w), 1765 (s), 1677 (vs), 1650 (w), 1418 (w), 1324 (w), 1305 (m), 1278 (m), 1223 (w), 1204 (w), 1194 (w), 947 (w), 799 (w), 764 (w), 657 (w), 517 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 316 nm (2.86), 264 (3.59).

MS (EI, 70eV): *m*/*z* (%): 332 (25) [M^+], 298 (20), 296 (45), 268 (15), 247 (14), 166 (29), 138 (14), 131 (100), 103 (44), 77 (39), 51 (12).

HRMS ($C_{18}H_{14}O_2Cl_2$) calc. = 332.03708, found = 332.03616 ± 1 ppm.

4.2.18: 4,12-Bis(azidocarbonyl)[2.2]paracyclophane (85)



To a suspension of 4,12-bis(chlorocarbonyl)[2.2]paracyclophane (**84**, 0.42 g, 1.265 mmol) in 15 mL of acetone was slowly added a solution of sodium azide (0.82 g, 12.65 mmol) in 15 mL of water, over a period of 10 min. The reaction mixture was warmed to 50 °C and stirring continued at this temperature for 5 h. At the end of the reaction 100 mL of icecold water was added, the formed precipitate was filtered off, and air dried to give (**85**, 0.33 g, 0.95 mmol) as colourless amorphous material in 76% yield.

R_f : decomposes on TLC (SiO_2).

m.p.: 110 °C.

^{1}H NMR (200.1 MHz, $CDCl_3$): δ = 7.15 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.9 Hz, 5-H, 13-H), 6.75 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.9 Hz, $J_{7\text{-H},8\text{-H}} = J_{15\text{-H},16\text{-H}}$ = 7.8 Hz, 7-H, 15-H), 6.52 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{16\text{-H},15\text{-H}}$ = 7.8 Hz, 8-H, 16-H), 4.20 – 4.08 (m, 2 H, bridge-H), 3.23 – 3.00 (m, 4 H, bridge-H), 2.96 – 2.85 (m, 2 H, bridge-H).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 143.3 (s, Ar), 141.0 (s, Ar), 136.0 (d, Ar), 135.6 (d, Ar), 135.1 (d, Ar), 131.0 (s, Ar), 34.9 (t, bridge), 34.1 (t, bridge); due to weak intensity the carbonyl carbon atom was not detected.

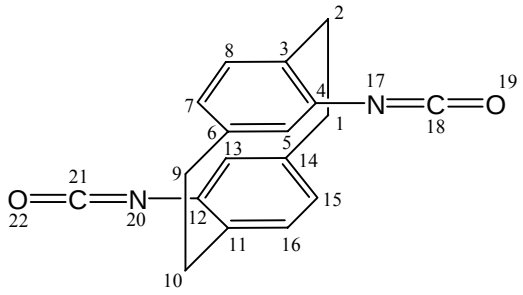
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 2989 (w), 2950 (w), 2929 (w), 2896 (w), 2853 (w), 2137 (vs), 1679 (vs), 1538 (w) 1245 (vs), 1189 (vs), 1127 (w), 998 (s), 878 (w), 823 (w), 699 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 322 nm (3.33), 268 (4.29).

MS (EI, 70eV): *m*/*z* (%) = 346 (1) [M^+], 318 (2) ($C_{18}H_{14}N_4O_2$), 290 (30) ($C_{18}H_{14}N_2O_2$), 263 (6), 145 (100) (C_9H_7NO), 131 (12) (C_9H_7O), 116 (12), 90 (32), 77 (9), 44 (9).

HRMS ($C_{18}H_{14}N_6O_2$) not available due to very low intensity of [M^+].

4.2.19: 4,12-Diisocyanato[2.2]paracyclophane (23)



The crude 4,12-bis(azidocarbonyl)[2.2]paracyclophane (**85**, 0.42 g, 1.21 mmol) was dissolved in 50 mL of anhydrous toluene under N_2 and the mixture refluxed for 1 h. The solvent was evaporated *in vacuo* and the crude pale yellow solid of 0.34 g was subjected to column chromatography using a 1:4 mixture of CH_2Cl_2 and pentane on silica gel yielding 4,12-diisocyanato[2.2]paracyclophane (**23**, 0.100 g, 0.345 mmol, 30%) as colourless crystalline solid. Recrystallisation from CH_2Cl_2 and pentane by the slow diffusion method gave colourless plates suitable for X-ray analysis.

R_f : 0.72 (SiO_2, 3:7 EtOAc/pentane).

m.p.: 156 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.77 (dd, 2 H, $J_{7\text{-H},5\text{-H}} = J_{15\text{-H},13\text{-H}}$ = 1.83 Hz, $J_{7\text{-H},8\text{-H}} = J_{15\text{-H},16\text{-H}}$ = 7.91 Hz, 7-H, 15-H), 6.37 (d, 2 H, $J_{8\text{-H},7\text{-H}} = J_{16\text{-H},15\text{-H}}$ = 7.91 Hz, 8-H, 16-H), 5.89 (d, 2 H, $J_{5\text{-H},7\text{-H}} = J_{13\text{-H},15\text{-H}}$ = 1.74 Hz, 5-H, 13-H), 3.33 – 3.26 (m, 2 H, 2-H, 10-H), 3.04 – 2.92 (m, 4 H, 1-H, 9-H), 2.72 – 2.64 (m, 2 H, 2-H, 10-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 178.5 (s, C-18, C-21), 140.9 (s, C-6, C-14), 133.8 (s, C-4, C-12), 133.7 (d, C-8, C-16), 133.5 (s, C-3, C-11), 131.7 (d, C-5, C-13), 126.7 (d, C-7, C-15), 33.2 (t, C-1, C-9), 32.0 (t, C-2, C-10).

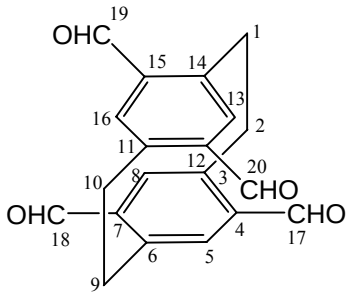
IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 2964 (w), 2927 (w), 2850 (w), 2272 (vs), 2253 (vs), 1559 (w), 1507 (w), 1262 (w), 1072 (w), 867 (w), 720 (w), 628 (w), 563 (w), 440 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 294 nm (2.97), 270 (3.26).

MS (EI, 70eV): *m*/*z* (%) = 290 (25) [M^+], 258 (8), 256 (21), 160 (12), 145 (100), 128 (12), 90 (15), 71 (15), 57 (25), 44 (20).

HRMS ($C_{18}H_{14}N_2O_2$) calc. = 290.105527, found = 290.10552 ± 3 ppm.

4.2.20: 4,7,12,15-Tetraformyl[2.2]paracyclophane (29)



A dried, N_2 flushed 250 mL Schlenk flask with magnetic stirrer was charged with 4,7,12,15-tetrabromo[2.2]paracyclophane (**89**, 0.100 g, 0.19 mmol) (note: the compound was dried under high vacuum at 70 °C for 2 h) along with 100 mL of dry ether. To this solution was added *n*-BuLi (0.977 g, 15.26 mmol) (the quality of *n*-BuLi was important, it has to be a clear colourless solution) slowly over a period of 5 min at room temperature. The reaction mixture was stirred at room temperature for 6 h, before dry (<50ppm of water) DMF (1.11 g, 15.26 mmol) was added slowly also at room temperature (note: exothermic reaction). The reaction mixture was stirred at room temperature overnight. The mixture was quenched by adding water, the organic layer was separated, and the water layer was extracted with ether. The combined organic phase was washed with water, 2 N aq. HCl, sat. aq. $NaHCO_3$, brine and dried with anhydrous $MgSO_4$. The solvent was evaporated under reduced pressure and the compound was precipitated from CH_2Cl_2/pentane mixture yielding (**29**, 0.05 g, 0.156 mmol) in 83% as a pale yellow solid.

Note: The yield of this reaction varied between 50-80%. The yield mentioned above amounts to the maximum obtained.

R_f : 0.4 (SiO_2, 1:1 EtOAc/hexane).

m.p.: >260 °C (decomp.)

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 9.95 (s, 4 H, 17-H, 18-H, 19-H, 20-H), 6.99 (s, 4 H, 5-H, 8-H, 13-H, 16-H), 4.19 – 4.12 (m, 4 H, bridge-H), 3.16 – 3.09 (m, 4 H, bridge-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 191.1 (d, C-17, C-18, C-19, C-20), 141.3 (s, Ar), 139.4 (s, Ar), 137.8 (d, C-5, C-8, C-13, C-16), 33.2 (t, C-1, C-2, C-9, C-10).

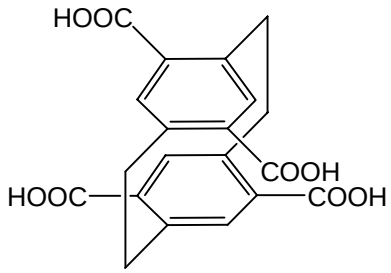
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2858 (w), 2755 (w), 1683 (vs), 1589 (w), 1547 (w), 1205 (w), 1170 (m), 934 (w), 868 (w), 774 (m), 718 (m), 536 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 313 nm (3.71).

MS (EI, 70eV): *m*/*z* (%) = 320 (64) [M^+], 302 (40), 292 (46), 274 (16), 264 (17), 160 (26), 132 (100), 104 (60), 78 (36), 63 (8).

HRMS ($C_{20}H_{16}O_4$) calc. = 320.10486, found = 320.10461 ± 1 ppm.

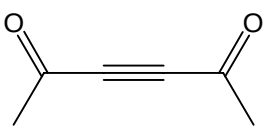
4.2.21: 4,7,12,15-Tetracarboxy[2.2]paracyclophane (90)



To a suspension of 4,7,12,15-tetraformyl[2.2]paracyclophane (**29**, 0.035 g, 0.109 mmol) in 10 mL of *t*-BuOH and 6 mL of 2-methyl-2-butene was slowly added a solution of a mixture of $NaClO_2$ (0.32 g, 3.5 mmol) and $NaH_2PO_4.H_2O$ (0.31 g, 2.2 mmol) in 10 mL of water with stirring. The reaction was continued overnight whilst stirring at room temperature. The solvent was evaporated under vacuum, and the crude was dried under high vacuum. **90** was found to be highly insoluble in all organic solvents (CH_2Cl_2, $CHCl_3$, DMSO, acetone) and was well soluble in water. Hence separation of **90** from the inorganic reactants was impossible. The ^{1}H NMR spectrum was recorded using the crude impure sample.

^{1}H NMR (400.1 MHz, D_2O): δ = 7.05 (s, 4 H, Ar-H), 3.74 – 3.66 (m, 4 H, bridge-H), 2.93 – 2.85 (m, 4 H, bridge-H).

4.2.22: 3-Hexyne-2,5-dione (111)[43]



Preparation of Jones reagent: 23.5 g of CrO_3 was dissolved in 21 mL of conc. H_2SO_4 with cooling, and the solution diluted with 150 mL of distilled water. The total volume should not exceed 175 mL.

The Jones reagent was subsequently added dropwise with stirring to a solution of 3-hexyne-2,5-diol (**110**, 15 g, 133.9 mmol) in acetone (400 mL, analytical grade). After completion of

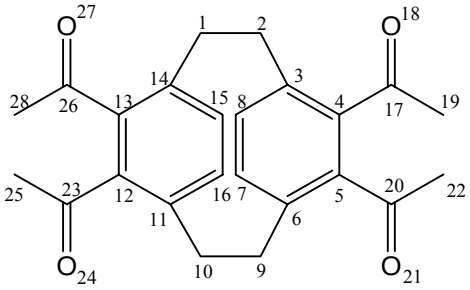
the addition the reaction was quenched by adding 5 mL of methanol and stirring was continued for a further 30 min period. The reaction was allowed to stand for 30 min during which the layers separated. The top acetone layer (also containing water) was decanted and concentrated under reduced pressure (the water bath of the rotary evaporator was kept at 25 °C) and subsequently extracted with ether. The ether phase was washed with water, sat. aq. $NaHCO_3$ solution (important as the acid present in the reaction mixture catalyses the decomposition of the hexynedione), brine solution and dried with anhydrous $MgSO_4$. An orange oil was obtained, which was subjected to high vacuum distillation (0.3 mm of Hg) at 50 °C yielding **111** as pale yellow oil (3.42 g, 31.09 mmol, 23%).

Lit. b.p: 50 °C/0.2 mm of Hg[43]

^{1}H NMR (200.1 MHz, $CDCl_3$): δ = 2.43 (s, CH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 183.1 (s, C=O), 84.1 (s, C≡C), 32.3 (q, CH_3).

4.2.23: 4,5,12,13-Tetraacetyl[2.2]paracyclophane (30)



A N_2-flushed, dried reaction flask fitted with a reflux condenser was charged with the bisallene (**92**, 0.85 g, 10.91 mmol) and 3-hexyne-2,5-dione (**111**, 1.0 g, 9.09 mmol) at room temperature. The reaction mixture was warmed to 45 °C and maintained for 5 h during which time a precipitate fell out. The temperature was gradually raised to 75 °C and stirring was continued for another 20 h. For work-up, the solvent was evaporated *in vacuo* yielding a viscous reddish brown crude product which was subjected to silica gel column chromatography with 2:3 EtOAc/hexane, yielding the tetraacetylphane **30** as a yellow solid. It was washed with diethylether to furnish the tetraacetyl cyclophane as colourless crystalline solid (0.42 g, 1.11 mmol) in 12% yield (based on hexynedione). Single crystals (plates) for X-ray analysis were obtained by the slow diffusion method using a CH_2Cl_2/pentane mixture.

R_f : 0.45 (SiO_2, 1:1 EtOAc/hexane).

m.p.: >184 °C (decomposes).

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.75 (s, 4 H, 7-H, 8-H, 15-H, 16-H), 3.11 – 3.08 (m, 8 H, 1-H, 2-H, 9-H, 10-H), 2.32 (s, 12 H, 19-H, 22-H, 25-H, 28-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 203.4 (s, C-17, C-20, C-23, C-26), 139.1 (s, C-3, C-6, C-11, C-14), 137.7 (s, C-4, C-5, C-13, C-23), 33.8 (t, C-1, C-2, C-9, C-10), 32.1 (q, C-19, C-22, C-25, C-28).

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3443 (w), 2941 (w), 2860 (w), 1688 (vs), 1405 (w), 1352 (m), 1255 (s), 1116 (w), 1091 (w), 854 (w), 617 (w), 510 (w).

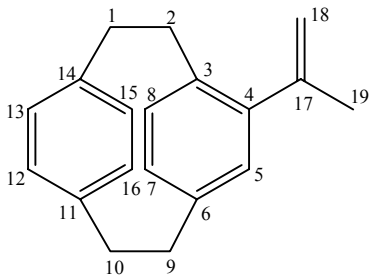
UV/Vis (CH_3CN): λ_{max} (lg ε) = 312 nm (3.36), 290 (3.43), 276 (3.58), 264 (3.79).

MS (EI, 70eV): *m*/*z* (%) = 376 (75) [M^+], 361 (80), 343 (18), 333 (22), 315 (16), 297 (16), 190 (35), 187 (100), 173 (35), 160 (82), 145 (45), 128 (40), 117 (50), 115 (75), 91 (35), 77 (20), 51 (15), 43 (75).

HRMS ($C_{24}H_{24}O_4$) calc. = 376.167459, found = 376.16733 ± 1 ppm.

Elemental analysis: calc. = C 76.57, H 6.43; found = C 75.71, H 6.47.

4.2.24: 4-Isopropenyl[2.2]paracyclophane (114)[66]



A dried, N_2-flushed Schlenk flask was charged with $MePPh_3Br$ (0.34 g, 0.96 mmol) along with 25 mL of anhydrous THF, and the mixture was cooled to -78 °C. *n*-BuLi (0.06 g, 0.96 mmol) was added slowly and the reaction mixture was stirred for 10 min at 0 °C. The mixture was transferred to another flask containing 4-acetyl[2.2]paracyclophane (**113**, 0.200 g, 0.8 mmol) in 25 mL of THF, also cooled to -78 °C. The reaction mixture was allowed to warm to room temperature and stirring continued for 24 h. At the end of the reaction, ice cold water (20 mL) was added and the mixture was extracted with CH_2Cl_2. The organic phase was washed with water, sat. aq. $NaHCO_3$ solution, brine solution and dried with anhydrous $MgSO_4$. The solvent was evaporated under vacuum and the crude was flash chromatographed

on silica gel and 1:9 CH_2Cl_2/pentane as eluent yielding the desired compound **114** (0.079 g, 0.32 mmol) as colourless amorphous solid in 40% yield.

R_f : 0.37 (SiO_2, 1:9 CH_2Cl_2/pentane).

m.p.: 50 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.57 (dd, 1 H, *J* = 1.74 Hz, *J* = 7.91 Hz, Ar-H), 6.53 (dd, 1 H, *J* = 1.72 Hz, *J* = 7.75 Hz, Ar-H), 6.49 (dd, 1 H, *J* = 1.76 Hz, *J* = 7.78 Hz, Ar-H), 6.35 (d, 1 H, *J* = 7.62 Hz, 8-H), 6.34 – 6.28 (m, 3 H, Ar-H), 5.12 – 5.11 (m, 1 H, 18-H), 5.07 – 5.06 (m, 1 H, 18-H), 3.32 – 3.27 (m, 1 H, 2-H), 3.03 – 2.85 (m, 7 H, 1-H, 2-H, 9-H, 10-H), 2.00 (dd, 3 H, *J* = 0.84 Hz, *J* = 1.33 Hz, 19-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 145.4 (s, Ar), 142.9 (s, C-4), 139.7 (s, Ar), 139.3 (s, Ar), 139.2 (s, Ar), 135.4 (d, Ar), 132.9 (d, Ar), 132.3 (d, Ar), 132.2 (d, Ar), 132.1 (d, Ar), 130.6 (d, Ar), 130.1 (d, Ar), 115.3 (t, C-18), 35.4, 35.2, 35.1 (t, C-1, C-9, C-10), 34.4 (t, C-2), 23.9 (q, C-19).

IR (KBr): $\tilde{\nu}$ [cm^{-1}] = 3005 (m), 2952 (m), 2850 (m), 1899 (w), 1623 (w), 1587 (w), 1500 (w), 1451 (w), 1433 (w), 1369 (w), 1177 (w), 1076 (w), 942 (vs), 895 (m), 793 (m), 714 (s), 645 (s), 598 (w).

UV/Vis (CH_2Cl_2): λ_{max} (lg ε) = 290 nm (2.97), 284 (3.18), 274 (3.36).

MS (EI, 70eV): *m*/*z* (%) = 249 (3) [MH^+], 248 (20) [M^+], 143 (100), 129 (50), 128 (35), 105 (16), 77 (6), 51 (4), 44 (7).

HRMS ($C_{19}H_{20}$) calc. = 248.156500, found = 248.15654 ± 2 ppm.

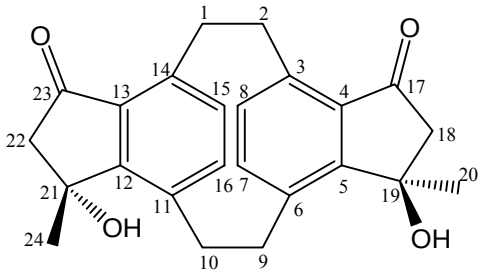
4.2.25: Aldol condensation of 4,5,12,13-tetraacetyl[2.2]paracyclophane (30)

(a) A dried, N_2-flushed Schlenk flask was charged with 0.40 g of NaOH and 10 mL of anhydrous methanol and the mixture was cooled in an ice water bath under stirring. After all the NaOH had dissolved, the water bath was removed and 4,5,12,13-tetraacetyl[2.2]paracylophane (**30**, 0.1 g, 0.26 mmol) was added in one portion and the mixture was stirred at room temperature. During 15 min the colour turned to turbid yellow, then to brown, and at the end to reddish brown. The reaction mixture was stirred at room temperature for 24 h, and was then quenched by adding water followed by CH_2Cl_2. One of the products namely, the *anti*-isomer **35** precipitated, it was removed by filtration and dried yielding a pale brown solid (0.07 g, 0.19 mmol) in 70% yield. The rest of the filtrate was extracted with CH_2Cl_2. The organic phase was washed several times with water, brine and finally dried with anhydrous $MgSO_4$ and the solvent was removed by rotary evaporation

yielding the *syn*-isomer **34** also as pale brown solid (0.03 g, 0.079 mmol) in 30%. Compound **34** was crystallised from chloroform to furnish plate-like crystals used for X–ray structural analysis.

(b) A N_2-flushed 25 mL round-bottomed flask was charged with 4,5,12,13-tetraacetyl[2.2]paracyclophane (**30**, 0.100 g, 0.266 mmol) along with 10 mL of anhydrous methanol and aniline (2.28 g, 26.59 mmol) with stirring at room temperature. The stirring was continued at the same temperature for 8 d avoiding exposure to light. For workup the solvent was evaporated under reduced pressure followed by adding diethylether. The precipitate formed was filtered off and was found to be the *anti*-isomer **35** (0.040 g, 0.106 mmol) as a brown solid in 40% yield. The filtrate was washed with 2 N aq. HCl solution, sat. aq. $NaHCO_3$ solution, brine and dried with anhydrous $MgSO_4$. The solvent was removed by rotary evaporation. The crude product was subjected to flash column chromatography on silica gel and 1:1 EtOAc/hexane mixture furnishing the *syn*-isomer **34** (0.020 g, 0.0532 mmol) in 20% yield as colourless solid.

syn(_endo_,_endo_)-19,21-Dihydroxy-19,21-dimethyl[2.2]indanonophane-17,23-dione (34)



R_f : 0.29 (SiO_2, 1:1 EtOAc/pentane).

m.p.: >255 °C (decomp.)

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.92 (d, 2 H, *J* = 7.63 Hz, Ar-H), 6.36 (d, 2 H, *J* = 7.62 Hz, Ar-H), 4.13 – 4.05 (m, 2 H, bridge-H), 3.62 – 3.54 (m, 2 H, bridge-H), 3.13 – 3.07 (m, 2 H, bridge-H), 2.98 – 2.91 (m, 2 H, bridge-H), 2.82 (d, 2 H, J_{gem} = 18.32 Hz, 18-H, 22-H), 2.68 (d, 2 H, J_{gem} = 18.30 Hz, 18-H, 22-H), 1.99 (br.s, 2 H, OH), 1.47 (s, 6 H, 20-H, 24-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 203.1 (s, C-17, C-23), 155.7 (s, Ar), 140.7 (s, Ar), 140.6 (d, Ar), 137.2 (s, Ar), 136.5 (s, Ar), 133.5 (d, Ar), 74.9 (s, C-19, C-21), 54.6 (t, C-18, C-22), 33.0 (t, bridge), 32.2 (q, C-20, C-24), 30.2 (t, bridge).

IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3479 (m), 2975 (w), 2887 (w), 1668 (vs), 1559 (m), 1484 (w), 1450 (w), 1367 (w), 1244 (m), 1061 (m), 1040 (w), 954 (w), 873 (w), 603 (m), 558 (w).

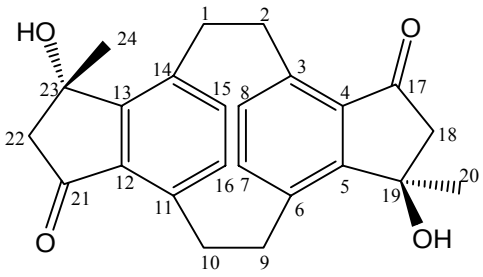
UV/Vis (CH_2Cl_2): λ_{max} (lg ε) = 330 nm (2.87), 288 (3.65).

MS (EI, 70eV): *m*/*z* (%) = 376 (1) [M^+], 358 (39), 340 (53), 325 (15), 312 (10), 297 (13), 187 (12), 170 (100), 142 (36), 141 (35), 128 (10), 115 (25), 91 (8), 77 (5), 63 (5), 51 (5), 40 (5).

HRMS ($C_{24}H_{23}O_4$) $[M-H]^+$ calc. = 375.1596, found = 375.15942 ± 2 ppm.

Elemental analysis: calc. = C 76.57, H 6.43; found = C 74.60, H 6.20.

***anti*(*endo*,*endo*)-19,23-Dihydroxy-19,23-dimethyl[2.2]indanonophane-17,21-dione (35)**



R_f : 0.36 (SiO_2, 1:1 EtOAc/pentane).

m.p.: >380 °C.

^{1}H NMR (400.1 MHz, DMSO-d_6): δ = 6.85 (d, 2 H, ^3J = 7.57 Hz, Ar-H), 6.43 (d, 2 H, ^3J =7.59 Hz, Ar-H), 5.61 (br.s, 2 H, OH), 4.00 – 3.95 (m, 2 H, bridge-H), 3.76 – 3.70 (m, 2 H, bridge-H), 3.05 – 2.96 (m, 2 H, bridge-H), 2.92 – 2.88 (m, 2 H, bridge-H), 2.84 (d, 2 H, ^2J = 18.25 Hz, 18-H, 22-H), 2.63 (d, 2 H, ^2J = 18.21 Hz, 18-H, 22-H), 1.36 (s, 6 H, 20-H, 24-H).

^{13}C NMR (100.6 MHz, DMSO-d_6): δ = 203.5 (s, C-17, C-21), 157.5 (s, C-19, C-23), 139.3 (s, Ar), 138.7 (d, Ar), 136.7 (s, Ar), 135.4 (s, Ar), 134.6 (d, Ar), 133.0 (s, Ar), 54.3 (t, C-18, C-22), 31.7 (q, C-20, C-24), 31.1, 30.3 (t, C-1, C-2, C-9, C-10).

IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3428 (w), 2960 (w), 2983 (w), 1674 (s), 1588 (w), 1558 (w), 1250 (w), 1113 (w), 1067 (w), 870 (w), 604 (w).

UV/Vis (MeOH): λ_{max} (lg ε) = 292 nm (3.06).

MS (EI, 70eV): *m*/*z* (%): 376 (2) [M^+], 358 (20), 340 (44), 325 (15), 312 (17), 297 (16), 170 (100), 141 (52), 115 (28), 93 (34), 77 (6), 63 (6), 42 (4).

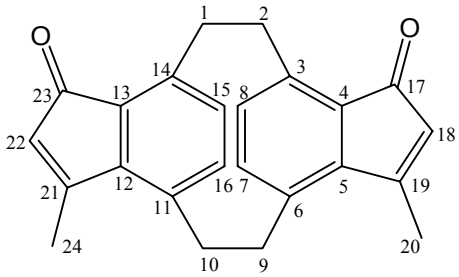
HRMS ($C_{24}H_{24}O_4$) calc. = 376.16748, found = 376.16628 ± 1 ppm.

Elemental analysis: calc. = C 76.57, H 6.43; found = C 75.06, H 6.30.

4.2.26: Dehydration reaction of 34

A dried, N_2-flushed round-bottomed flask was charged with (**34**, 0.03 g, 0.0798 mmol) along with 15 mL of anhydrous toluene and a pinch of *p*-TsOH. The mixture was stirred at room temperature for 6 h, the solvent was removed under reduced pressure, and the crude product was subjected to preparative TLC on silica gel with 1% EtOAc in CH_2Cl_2 resulting in three isomers: derivative **36** (~0.01 g, 0.029 mmol, 30%) as a yellow solid, **129** (~0.01 g, 0.029 mmol, 30%) as a yellow solid and **130** (0.01 g, 0.029 mmol, 37%) as a colourless solid.

***syn*-19,21-Dimethyl[2.2]indenonophane-17,23-dione (36)**



R_f : 0.53 (SiO_2, 1:1 EtOAc/hexane).

m.p.: 150 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.39 (d, 2 H, *J* = 8.07 Hz, Ar-CH), 6.22 (d, 2 H, *J* = 8.06 Hz, Ar-CH), 5.61 (q, 2H, *J* = 1.57 Hz, 18-H, 22-H), 3.95 – 3.88 (m, 2 H, bridge-H), 3.48 – 3.40 (m, 2 H, bridge-H), 2.75 – 2.62 (m, 4 H, bridge-H), 2.30 (d, 6 H, *J* = 1.58 Hz, 20-H, 24-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 203.8 (s, C-17, C-23), 167.4 (s, C-19, C-21), 140.5 (s, Ar), 136.5 (d, Ar), 134.5 (s, Ar), 133.4 (d, Ar), 125.7 (d, C-18, C-22), 33.4 (t, bridge), 29.2 (t, bridge), 17.2 (q, C-20, C-24); two aromatic quaternary carbons not detected due to low intensity.

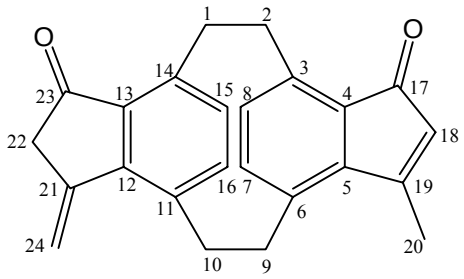
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2922 (m), 2852 (w), 1688 (vs), 1562 (m), 1430 (m), 1251 (w), 1214 (w), 1051 (s), 827 (m), 795 (m), 626 (m), 558 (m).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 363 nm (3.09), 252 (4.17).

MS (EI, 70eV): *m*/*z* (%) = 340 (100) [M^+], 325 (17), 312 (12), 297 (20), 269 (7), 170 (100), 141 (44), 115 (16), 43 (8).

HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14509 ± 1 ppm.

***syn*-19-Methyl-21-methylene[2.2]indano-18-enophane-17,23-dione (129)**



R_f : 0.53 (SiO_2, 1:1 EtOAc/hexane).

m.p.: 195 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.77 (d, 1 H, *J* = 7.59 Hz, Ar-H), 6.44 (d, 1 H, *J* = 7.59 Hz, Ar-H), 6.39 (d, 1 H, *J* = 8.09 Hz, Ar-H), 6.12 (d, 1 H, *J* = 8.09 Hz, Ar-H), 5.78 (t, 1 H, *J* = 1.83 Hz, 24-H), 5.60 (q, 1 H, *J* = 1.59 Hz, 18-H), 5.39 (t, 1 H, *J* = 1.55 Hz, 24-H), 4.11 – 4.06 (m, 1 H, bridge-H), 3.88 – 3.77 (m, 2 H, bridge-H), 3.35 – 3.29 (m, 1 H, bridge-H), 3.12 (s, 2 H, 22-H), 3.09 – 2.97 (m, 1 H, bridge-H), 2.89 – 2.71 (m, 3 H, bridge-H), 2.30 (d, 3 H, *J* = 1.65 Hz, 20-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 203.3 (s, C-17, C-23), 162.8 (s, C-19), 151.5 (s, C-21), 146.7 (s, Ar), 141.5 (s, Ar), 140.4 (s, Ar), 138.2 (s, Ar), 138.1 (s, Ar), 137.7 (d, Ar), 137.0 (s, Ar), 136.4 (d, Ar), 135.0 (s, Ar), 134.9 (d, Ar), 133.1 (s, Ar), 132.4 (d, Ar), 125.9 (d, C-18), 111.7 (t, C-24), 43.6 (t, C-22), 43.5 (t, C-1, C-2), 35.54 (t, bridge), 35.55 (t, bridge), 30.4 (q, C-20).

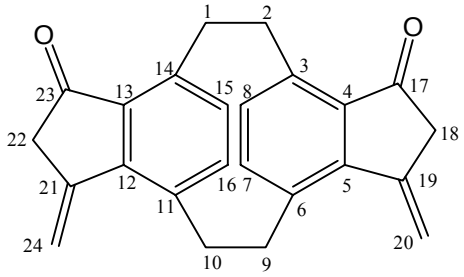
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2930 (w), 2851 (w), 1695 (s), 1556 (m), 1428 (w), 1391 (w), 1259 (m), 1214 (w), 1096 (w), 1049 (m), 1011 (m), 866 (m), 801 (m), 784 (m), 621 (w), 606 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 350 nm (3.27), 249 (4.35).

MS (EI, 70eV): *m*/*z* (%) = 340 (67) [M^+], 322 (16), 297 (10), 170 (100), 141 (44), 115 (17), 43 (5).

HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14536 ± 1 ppm.

***syn*-19,21-Dimethylene[2.2]indanonophane-17,23-dione (130)**



R_f : 0.53 (SiO_2, 1:1 EtOAc/hexane).

m.p.: >195 °C decomposes.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.70 (d, 2 H, *J* = 7.61 Hz, Ar-H), 6.34 (d, 2 H, *J* = 7.56 Hz, Ar-H), 5.79 (s, 2 H, 20-H, 24-H), 5.39 (s, 2 H, 20-H, 24-H), 4.08 – 4.01 (m, 2 H, bridge-H), 3.69 – 3.63 (m, 2 H, bridge-H), 3.08 (d, 4 H, *J* = 1.81 Hz, 18-H, 22-H), 2.92 – 2.85 (m, 2 H, bridge-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 202.6 (s, C-17, C-23), 151.7 (s, C-19, C-21), 140.8 (s, Ar), 140.6 (s, Ar), 139.9 (s, Ar), 136.5 (d, Ar), 135.9 (s, Ar), 132.0 (d, Ar), 111.4 (t, C-20, C-24), 42.9 (t, C-18, C-22), 31.4 (t, bridge), 30.1 (t, bridge).

IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2923 (m), 2852 (w), 1692 (vs), 1554 (w), 1459 (w), 1445 (w), 1379 (w), 1315 (w), 1252 (s), 1042 (m), 866 (m), 782 (m), 610 (m), 565 (m).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 247 nm (4.30).

MS (EI, 70eV): *m*/*z* (%) = 340 (64) [M^+], 322 (24), 312 (12), 170 (100), 141 (48), 115 (18), 57 (10), 41 (4).

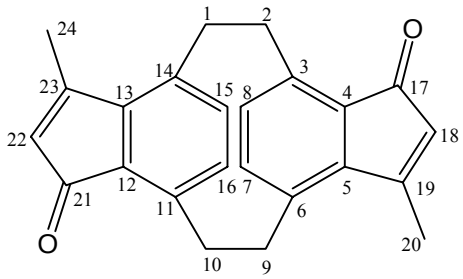
HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14556 ± 1 ppm.

4.2.27: Dehydration of 35

A dried N_2-flushed Schlenk flask with reflux condenser and a stirrer was charged with **35** (0.07 g, 0.186 mmol) along with 25 mL of anhydrous toluene and a pinch of *p*-TsOH. The reaction mixture was refluxed with stirring for 60 h, the reaction mixture was cooled to room temp., and the solvent was evaporated under reduced pressure. The crude was subjected to preparative TLC on silica gel with 17:3 CH_2Cl_2/pentane resulting in three isomers: derivative **135** (0.01 g, 0.029 mmol, 16%) as a yellow crystalline solid, **136** (0.03 g, 0.088 mmol, 48%) as a yellow solid, **137** (~0.01 g, 0.029 mmol, 16%) as a colourless solid. Compound **135** was

recrystallised from CH_2Cl_2/pentane by the slow diffusion method to furnish yellow tablet-like crystals used for X-ray analysis.

***anti*-19,23-Dimethyl[2.2]indenonophane-17,21-dione (135)**



R_f : 0.49 (SiO_2, 1:1 EtOAc/hexane).

m.p.: 253 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.36 (d, 2 H, *J* = 8.05 Hz, 8-H, 16-H), 6.26 (d, 2 H, *J* = 8.05 Hz, 7-H, 15-H), 5.60 (q, 2 H, *J* = 1.43 Hz, 18-H, 22-H), 4.01 – 3.96 (m, 2 H, 2-H, 10-H), 3.36 – 3.29 (m, 2 H, 1-H, 9-H), 2.94 – 2.86 (m, 2 H, 1-H, 9-H), 2.56 – 2.49 (m, 2 H, 2-H, 10-H), 2.32 (d, 6 H, *J* = 1.33 Hz, 20-H, 24-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 198.4 (s, C-17, C-21), 163.1 (s, C-19, C-23), 145.7 (s, C-5, C-13), 139.0 (s, C-3, C-11), 136.8 (d, C-7, C-15), 135.9 (s, C-6, C-14), 133.2 (d, C-8, C-16), 132.2 (s, C-4, C-12), 125.3 (d, C-18, C-22), 31.3 (t, C-2, C-10), 31.1 (t, C-1, C-9), 17.3 (q, C-20, C-24).

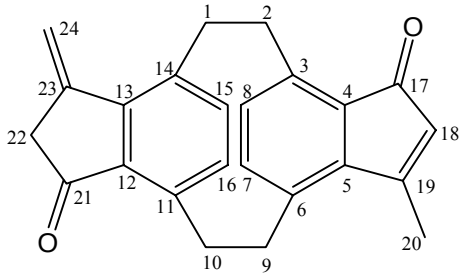
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2947 (w), 2928 (w), 1687 (vs), 1585 (w), 1558 (m), 1439 (w), 1424 (w), 1395 (w), 1271 (m), 1213 (w), 1029 (m), 1006 (m), 846 (s), 759 (m), 731 (m), 661 (m), 622 (s), 567 (m).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 389 nm (3.19), 356 (3.36), 251 (4.40).

MS (EI, 70eV): *m*/*z* (%) = 340 (59) [M^+], 325 (10), 312 (33), 297 (24), 170 (100), 141 (47), 115 (18), 57 (22), 43 (4).

HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14549 ± 1 ppm.

***anti*-19-Methyl-23-methylene[2.2]indano-18-enophane-17,21-dione (136)**



R_f : 0.49 (SiO_2, 1:1 EtOAc/hexane).

m.p.: >210 °C decomposes.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.61 (d, 1 H, *J* = 7.45 Hz, 15/16-H), 6.58 (d, 1 H, *J* = 7.63 Hz, 15/16-H), 6.32 (d, 1 H, *J* = 8.07 Hz, 8-H), 6.16 (d, 1 H, *J* = 8.08 Hz, 7-H), 5.84 (t, 1 H, *J* = 1.6 Hz, 24-H), 5.59 (q, 1 H, *J* = 1.5 Hz, 18-H), 5.38 (t, 1 H, *J* = 1.39 Hz, 24-H), 4.21 – 4.14 (m, 1 H, 1/10-H), 3.85 – 3.79 (m, 1 H, 2-H), 3.71 – 3.65 (m, 1 H, 1/10-H), 3.35 – 3.29 (m, 1 H, 9-H), 3.11 (t, 2 H, *J* = 1.43 Hz, 22-H), 3.06 – 3.01 (m, 1 H, 1/10-H), 2.94 – 2.81 (m, 2 H, 2-H, 9-H), 2.66 – 2.62 (m, 1 H, 1/10-H), 2.30 (d, 3 H, *J* = 1.49 Hz, 20-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 203.2 (s, C-17, C-21), 167.1 (s, C-12), 163.2 (s, C-19), 151.2 (s, C-13), 145.9 (s, C-5), 140.7 (s, C-23), 139.4 (s, C-11), 138.9 (s, C-3), 137.7 (d, C-15/16), 137.6 (s, C-14), 136.5 (d, C-7), 135.6 (s, C-6), 132.5 (s, C-4), 132.2 (d, C-15/16), 131.9 (d, C-8), 125.3 (d, C-18), 111.4 (t, C-24), 43.2 (t, C-22), 32.4 (t, C-1, C-10), 31.1 (t, C-9), 28.8 (t, C-2), 17.1 (q, C-20).

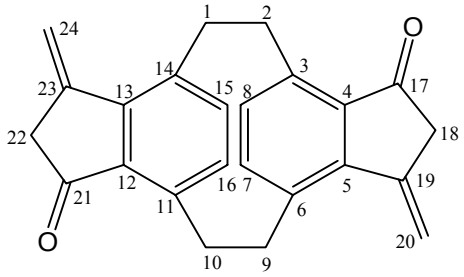
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2926 (w), 2852 (w), 1694 (s), 1555 (w), 1393 (w), 1261 (w), 1214 (w), 1050 (w), 1030 (w), 861 (w), 728 (w), 620 (w), 606 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 358 nm (3.25), 252 (4.35).

MS (EI, 70eV): *m*/*z* (%) = 340 (50) [M^+], 312 (12), 297 (12), 170 (100), 141 (40), 115 (19), 44 (16).

HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14527 ± 1 ppm.

***anti*-19,23-Dimethylene[2.2]indenonophane-17,21-dione (137)**



R_f : 0.49 (SiO_2, 1:1 EtOAc/hexane).

m.p.: >260 °C decomposes.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.62 (d, 2 H, *J* = 7.59 Hz, Ar-H), 6.55 (d, 2 H, *J* = 7.58 Hz, Ar-H), 5.89 (s, 2 H, 20-H, 24-H), 5.46 (s, 2 H, 20-H, 24-H), 4.11 – 4.06 (m, 2 H, bridge-H), 3.77 – 3.72 (m, 2 H, bridge-H), 3.15 (s, 4 H, 18-H, 22-H), 3.13 – 3.03 (m, 4 H, bridge-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 202.7 (s, C-17, C-21), 151.4 (s, C-19, C-23), 140.7 (s, Ar), 140.2 (s, Ar), 139.2 (s, Ar), 137.6 (d, Ar), 137.1 (s, Ar), 131.1 (d, Ar), 111.5 (t, C-20, C-24), 43.0 (t, C-18, C-22), 32.5 (t, bridge), 29.4 (t, bridge).

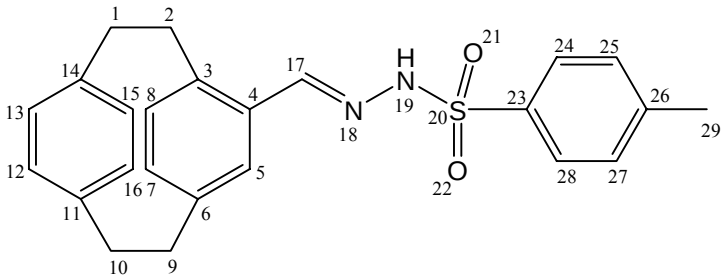
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 2925 (m), 2853 (w), 1693 (s), 1553 (w), 1456 (w), 1262 (w), 1239 (w), 1044 (w), 890 (w), 783 (w), 603 (w), 572 (w).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 343 nm (3.44), 242 (4.50).

MS (EI, 70eV): *m*/*z* (%) = 340 (52) [M^+], 322 (15), 312 (9), 170 (100), 141 (50), 115 (17), 97 (4), 71 (5), 57 (8), 49 (4).

HRMS ($C_{24}H_{20}O_2$) calc. = 340.14633, found = 340.14513 ± 1 ppm.

4.2.28: Tosylhydrazone of 4-formyl[2.2]paracyclophane (138)



To a solution of 4-formyl[2.2]paracyclophane (**87**, 0.5 g, 2.12 mmol) in 100 mL of anhydrous THF was added *p*-$TsNHNH_2$ (0.43 g, 2.33 mmol) and 0.05 g of *p*-TsOH, and the mixture refluxed for 2 h with stirring. The reaction mixture was cooled and the solvent was evaporated

under reduced pressure. The residue was taken up in CH_2Cl_2 and washed with water, the organic phase was dried with anhydrous $MgSO_4$, and the solvent was removed by rotary evaporation yielding the hydrazone **138** (0.85 g, 2.12 mmol) as colourless solid quantitatively.

R_f : 0.1 (SiO_2, CH_2Cl_2).

m.p.: 162 °C.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 8.35 (br.s, 1 H, 19-H), 7.98 (d, 2 H, $J_{24\text{-H},25\text{-H}} = J_{28\text{-H},27\text{-H}}$ = 8.35 Hz, 24-H, 28-H), 7.77 (s, 1 H, 17-H), 7.34 (d, 1 H, $J_{25\text{-H},24\text{-H}} = J_{27\text{-H},28\text{-H}}$ = 7.99 Hz, 27-H, 25-H), 6.78 (d, 1 H, $J_{5\text{-H},7\text{-H}}$ = 1.81 Hz, 5-H), 6.52 (dd, 1 H, $J_{7\text{-H},8\text{-H}}$ = 7.84 Hz, $J_{7\text{-H},5\text{-H}}$ = 1.89 Hz, 7-H), 6.45 (dd, 2 H, *J* = 3.92 Hz, *J* = 1.62 Hz, Ar-H), 6.42 (d, 1 H, $J_{8\text{-H},7\text{-H}}$ = 7.82 Hz, 8-H), 6.21 (dd, 1 H, *J* = 7.79 Hz, *J* = 1.46 Hz, Ar-H), 6.04 (dd, 1 H, *J* = 7.89 Hz, *J* = 1.62 Hz, Ar-H), 3.56 – 3.50(m, 1 H, 2-H), 3.12 – 2.97 (m, 5 H, 1-H, 9-H, 10-H), 2.36 (s, 3 H, 29-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 147.8 (d, C-17), 144.5 (s, C-26), 140.2 (s, Ar), 139.8 (s, C-3), 139.4 (s, Ar), 139.1 (s, Ar), 135.4 (s, C-23), 135.3 (d, C-8), 134.4 (d, C-7), 133.0 (d, Ar), 132.9 (s, Ar), 132.8 (d, Ar), 132.3 (s, C-5), 131.9 (d, Ar), 130.7 (d, Ar), 129.8 (d, C-25, C-27), 128.0 (d, C-24, C-28), 35.3 (t, C-1/10), 34.9 (t, C-1/10), 34.8 (t, C-9), 33.9 (t, C-2), 21.6 (q, C-29).

IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3145 (m), 2927 (w), 1594 (w), 1453 (w), 1367 (w), 1324 (s), 1164 (vs), 1052 (m), 956 (m), 917 (m), 804 (m), 694 (s), 663 (s), 572 (s).

UV/Vis (CH_3CN): λ_{max} (lg ε) = 298 nm (4.01).

(CH_2Cl_2): λ_{max} (lg ε) = 300 nm (4.02).

MS (EI, 70eV): *m*/*z* (%) = 404 (21) [M^+], 299 (28), 249 (32), 220 (32), 205 (30), 189 (17), 156 (17), 144 (56), 129 (44), 115 (100), 104 (72), 91 (90), 77 (32), 65 (52), 51 (25), 44 (11).

HRMS ($C_{24}H_{24}N_2O_2S$) calc. = 404.15585, found = 404.15469 ± 1 ppm.

4.2.29: 1,2-Bis-(4-[2.2]paracyclophanyl)ethane (140) and 1,2-bis-(4-[2.2]paracyclophanyl)ethene (40)

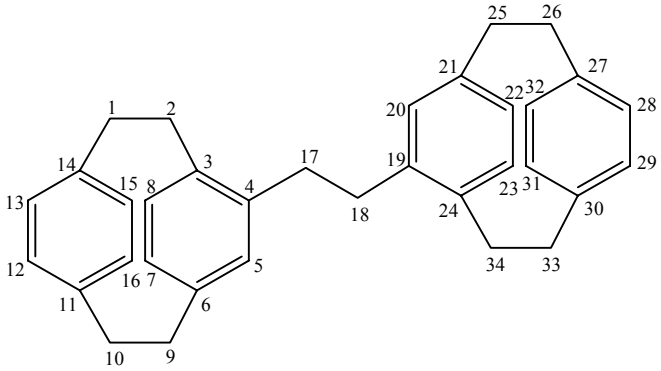
(a) A dried, N_2-flushed round bottomed flask equipped with reflux condenser and stirrer was charged with **138** (0.50 g, 1.23 mmol) along with 16 mL of anhydrous diglyme and *t*-BuOK (0.15 g, 1.36 mmol) with stirring. The reaction mixture became gold yellow clear solution. It was subjected to reflux for 4 h during which time the mixture turned to turbid red and then to pale yellow again. At the end the mixture was cooled and quenched by adding water. After extraction with ether and drying with anhydrous $MgSO_4$, the solvent was removed by rotary

evaporation. The crude was subjected to flash chromatography on silica gel with 3:2 CH_2Cl_2/pentane giving rise to a mixture of two compounds (highly fluorescent in UV) as colourless solids (0.03 g, 0.068 mmol) in 11% combined yield. Compound **140** is less soluble in CH_2Cl_2 than **40** and this was made use to obtain a pure sample of **140**. Crystallisation by slow diffusion of pentane into a solution of **140** in CH_2Cl_2 yielded plate-like crystals of X-ray quality. Compound **40** was not obtained in pure form.

(b) A dried, N_2-flushed round bottomed flask equipped with reflux condenser and stirrer was charged with **138** (9.35 g, 23.15 mmol) along with 60 mL of anhydrous diglyme and NaOMe (1.25 g, 23.15 mmol). The reaction mixture was refluxed for 2 h with stirring. The initial suspension after 5 min turned to turbid orange and then to a pale brown solution. The reaction mixture was cooled and cold water was added with stirring. The precipitate was filtered off, washed with water and dried giving rise to a pale yellow solid which was subjected to column chromatography on silica gel with 1:4 CH_2Cl_2/hexane providing a mixture of two compounds, **140** and **40**, as colourless solids (0.03 g) in 0.6% combined yield.

(c) To the crude 4-(1,1-dibromomethyl)[2.2]paracyclophane (**142**, 1.7 g, 4.49 mmol) in 50 mL of anhydrous ether under N_2 and cooled in an ice water bath, was added Zn powder (0.44 g, 6.73 mmol) and the suspension stirred vigorously at room temp. for 24 h. Reflux for 4 h completed the reduction. The reaction mixture was cooled, filtered, and the solvent evaporated under reduced pressure. The crude was taken up in water and extracted with CH_2Cl_2. The organic phase was dried with anhydrous $MgSO_4$ and the solvent was evaporated by rotary evaporation. The crude was subjected to flash chromatography on silica gel with 3% diethylether in pentane. A mixture of **140** and **40** was produced as colourless solids (0.020 g, 0.045 mmol, 2% combined yield).

(*meso*)1,2-Bis-(4-[2.2]paracyclophanyl)ethane (140)



R_f : 0.6 (SiO_2, 7:3 CH_2Cl_2/hexane).

m.p.: >260 °C (decomp.)

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 6.87 (dd, 2 H, $J_{7\text{-H},8\text{-H}} = J_{22\text{-H},23\text{-H}} = 7.84$ Hz, $J_{7\text{-H},5\text{-H}} = J_{22\text{-H},20\text{-H}} = 1.86$ Hz, 7-H, 22-H), 6.56 – 6.35 (m, 12-H, 5-H, 8-H, 12-H, 13-H, 15-H, 16-H, 20-H, 23-H, 28-H, 29-H, 31-H, 32-H), 3.57 (s, 2 H, bridge-H), 3.35 – 2.71 (m, 18 H, bridge-H).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 135.7, 135.3, 133.7, 132.4, 130.7, 128.6 (d, Ar), 39.3, 35.7, 35.4, 34.7, 34.2 (t, bridge); five quaternary carbons were not detected due to very low intensity as the concentration was very low.

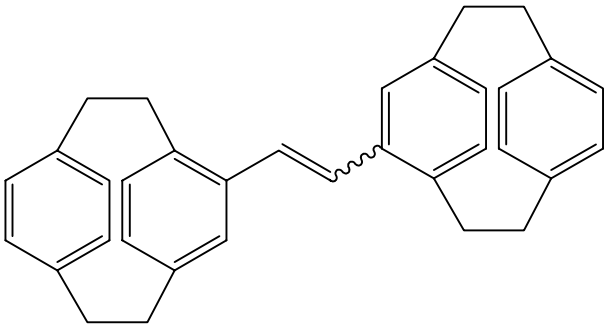
IR (Diamond-ATR): $\tilde{\nu}$ [cm^{-1}] = 3007 (w), 2923 (s), 2887 (m), 1890 (w), 1589 (m), 1498 (w), 1484 (w), 1432 (m), 1411 (m), 1204 (w), 1088 (w), 940 (s), 899 (s), 865 (s), 717 (vs), 646 (s), 606 (s), 588 (s).

UV/Vis (CH_2Cl_2): λ_{max} (lg ε) = 270 nm (2.59), 260 (3.56).

MS (EI, 70eV): *m*/*z* (%) = 442 (7) [M^+], 428 (44), 323 (51), 219 (48), 205 (100), 191 (48), 178 (12), 165 (10), 119 (28), 105 (19), 91 (10), 63 (5), 44 (8).

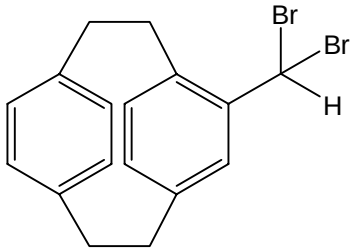
HRMS ($C_{34}H_{34}$) calc. = 442.26605, found = 442.26715 ± 1 ppm.

1,2-Bis-(4-[2.2]paracyclophanyl)ethene (40) (mixture of *cis* and *trans* isomers)[49]



GC-MS: 400 (100) [M^+], 335 (30), 231 (16), 217 (43), 202 (24), 117 (11), 105 (5), 91 (4), 44 (5).

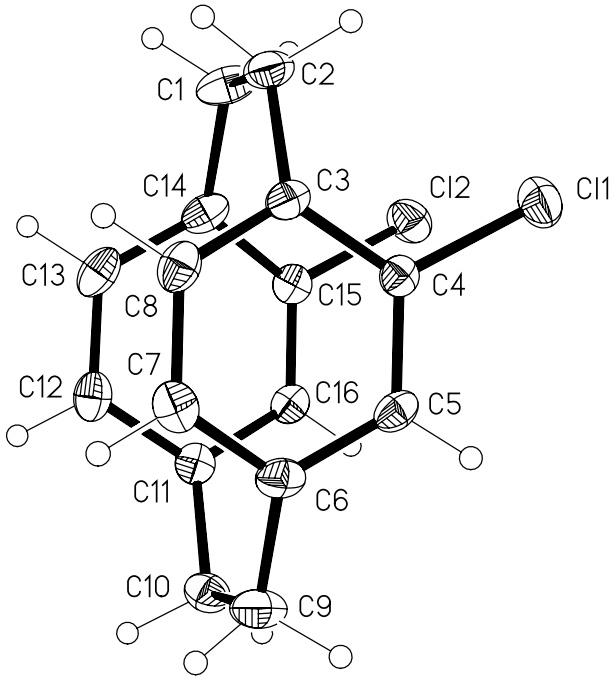
4.2.30: 4-(1,1-Dibromomethyl)[2.2]paracyclophane (142)



In a dried, argon purged flask, 4-formyl[2.2]paracyclophane (**87**, 0.50 g, 2.11 mmol) and triphenylphosphine (1.39 g, 5.29 mmol) were dissolved in 15 mL of anhydrous benzene. To this mixture was added 2,4,4,6-tetrabromo-2,5-cyclohexadienone[50] (**141**, 2.17 g, 5.29 mmol) with stirring. The reaction mixture refluxed for 18 h, while avoiding exposure to light. At the end of the reaction the precipitate formed was filtered off, washed with hexane and the combined filtrate was evaporated under vacuum yielding **142** as pale yellow viscous oil. **142** upon treatment with silica gel was found to undergo hydrolysis very rapidly liberating HBr and the starting material **87**. Also **142** was very unstable and hence no purification could be performed; **142** was hence used immediately for further reaction to prepare **140** and **40** (see above).

5. Single crystal X-ray structure data

5.1: 4,15-Dichloro[2.2]paracyclophane (19)



Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.5506 (4) Å	α= 90°
	b = 11.3311 (8) Å	β= 99.141(3) °
	c = 15.0074 (11) Å	γ = 90°
Volume, Z	1267.68 (15) $Å^3$, 4	

Bond lengths [Å]

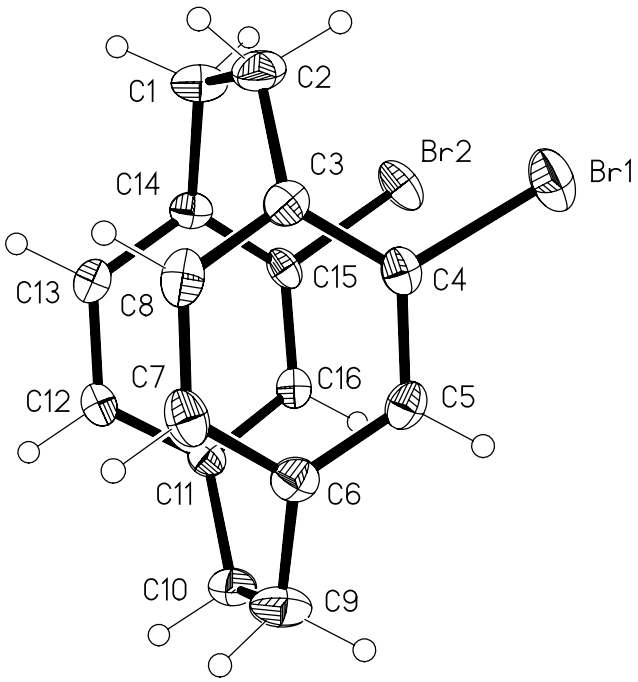
Cl(1)-C(4)	1.7428(11)	C(3)-C(8)	1.3988(17)
Cl(2)-C(15)	1.7508(12)	C(3)-C(4)	1.4021(15)
C(1)-C(14)	1.5110(17)	C(4)-C(5)	1.3886(15)
C(1)-C(2)	1.5860(18)	C(5)-C(6)	1.3953(17)
C(2)-C(3)	1.5087(16)	C(6)-C(7)	1.3921(17)

C(6)-C(9)	1.5087(17)	C(11)-C(12)	1.4012(16)
C(7)-C(8)	1.3891(17)	C(12)-C(13)	1.3932(19)
C(9)-C(10)	1.5886(17)	C(13)-C(14)	1.3974(18)
C(10)-C(11)	1.5127(17)	C(14)-C(15)	1.4021(16)
C(11)-C(16)	1.3971(16)	C(15)-C(16)	1.3888(16)

Bond angles [°]

C(14)-C(1)-C(2)	113.06(10)	C(6)-C(9)-C(10)	112.73(10)
C(3)-C(2)-C(1)	113.20(10)	C(11)-C(10)-C(9)	112.87(9)
C(8)-C(3)-C(4)	115.25(10)	C(16)-C(11)-C(12)	116.90(11)
C(8)-C(3)-C(2)	120.12(10)	C(16)-C(11)-C(10)	121.04(10)
C(4)-C(3)-C(2)	123.34(11)	C(12)-C(11)-C(10)	121.00(11)
C(5)-C(4)-C(3)	121.99(10)	C(13)-C(12)-C(11)	120.43(11)
C(5)-C(4)-Cl(1)	117.83(9)	C(12)-C(13)-C(14)	121.75(11)
C(3)-C(4)-Cl(1)	119.95(9)	C(13)-C(14)-C(15)	114.92(11)
C(4)-C(5)-C(6)	120.02(10)	C(13)-C(14)-C(1)	120.51(11)
C(7)-C(6)-C(5)	117.31(11)	C(15)-C(14)-C(1)	123.32(12)
C(7)-C(6)-C(9)	121.17(11)	C(16)-C(15)-C(14)	122.35(11)
C(5)-C(6)-C(9)	120.35(11)	C(16)-C(15)-Cl(2)	117.88(9)
C(8)-C(7)-C(6)	120.53(11)	C(14)-C(15)-Cl(2)	119.54(9)
C(7)-C(8)-C(3)	121.64(11)	C(15)-C(16)-C(11)	119.99(10)

5.2: 4,15-Dibromo[2.2]paracyclophane (20)



Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.6271 (15) Å	α= 90°
	b = 10.7919 (14) Å	β= 95.380 (9)°
	c = 16.498 (3) Å	γ = 90°
Volume, Z	1352.0 (4) $Å^3$, 4	

Bond lengths [Å]

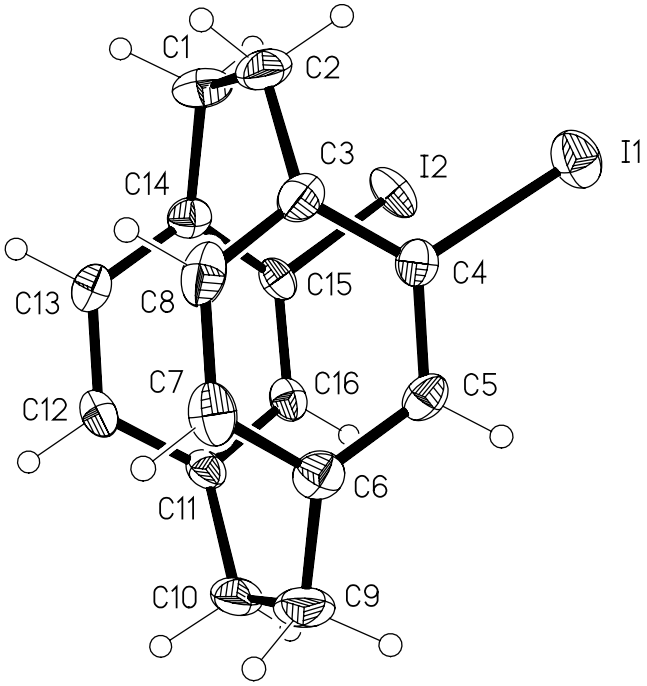
Br(1)-C(4)	1.9001(18)	C(4)-C(5)	1.391(3)
Br(2)-C(15)	1.9001(17)	C(5)-C(6)	1.394(3)
C(1)-C(14)	1.512(3)	C(6)-C(7)	1.397(3)
C(1)-C(2)	1.585(3)	C(6)-C(9)	1.512(3)
C(2)-C(3)	1.516(3)	C(7)-C(8)	1.397(3)
C(3)-C(8)	1.391(3)	C(9)-C(10)	1.577(3)
C(3)-C(4)	1.391(3)	C(10)-C(11)	1.518(2)

C(11)-C(12)	1.390(2)	C(13)-C(14)	1.392(3)
C(11)-C(16)	1.391(2)	C(14)-C(15)	1.400(3)
C(12)-C(13)	1.390(3)	C(15)-C(16)	1.396(2)

Bond angles [°]

C(14)-C(1)-C(2)	113.52(15)	C(6)-C(9)-C(10)	112.63(15)
C(3)-C(2)-C(1)	112.72(15)	C(11)-C(10)-C(9)	112.75(15)
C(8)-C(3)-C(4)	115.41(16)	C(12)-C(11)-C(16)	117.67(16)
C(8)-C(3)-C(2)	119.59(17)	C(12)-C(11)-C(10)	120.73(16)
C(4)-C(3)-C(2)	123.88(18)	C(16)-C(11)-C(10)	120.65(16)
C(5)-C(4)-C(3)	122.28(16)	C(11)-C(12)-C(13)	120.15(16)
C(5)-C(4)-Br(1)	117.36(13)	C(12)-C(13)-C(14)	121.84(16)
C(3)-C(4)-Br(1)	120.20(13)	C(13)-C(14)-C(15)	115.28(16)
C(4)-C(5)-C(6)	119.77(17)	C(13)-C(14)-C(1)	119.78(17)
C(5)-C(6)-C(7)	117.12(17)	C(15)-C(14)-C(1)	123.64(17)
C(5)-C(6)-C(9)	120.43(18)	C(16)-C(15)-C(14)	121.75(16)
C(7)-C(6)-C(9)	121.47(18)	C(16)-C(15)-Br(2)	117.66(13)
C(6)-C(7)-C(8)	120.14(17)	C(14)-C(15)-Br(2)	120.47(13)
C(3)-C(8)-C(7)	121.59(17)	C(11)-C(16)-C(15)	119.66(16)

5.3: 4,15-Diiodo[2.2]paracyclophane (21)



Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.662 (6) Å	α= 90°
	b = 11.069 (8) Å	β= 97.75 (7)°
	c = 17.014 (15) Å	γ = 90°
Volume, Z	1430 (2) $Å^3$, 4	

Bond lengths [Å]

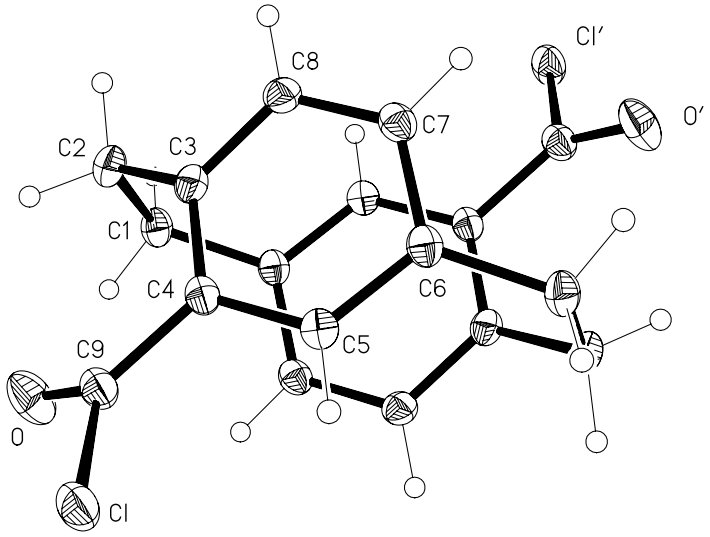
I(1)-C(4)	2.108(3)	C(4)-C(5)	1.386(3)
I(2)-C(15)	2.109(3)	C(5)-C(6)	1.399(4)
C(1)-C(14)	1.511(3)	C(6)-C(7)	1.398(4)
C(1)-C(2)	1.576(4)	C(6)-C(9)	1.515(4)
C(2)-C(3)	1.507(4)	C(7)-C(8)	1.383(4)
C(3)-C(4)	1.400(3)	C(9)-C(10)	1.579(4)
C(3)-C(8)	1.403(4)	C(10)-C(11)	1.509(4)

C(11)-C(12)	1.393(3)	C(13)-C(14)	1.399(4)
C(11)-C(16)	1.400(3)	C(14)-C(15)	1.403(3)
C(12)-C(13)	1.388(4)	C(15)-C(16)	1.395(3)

Bond angles [°]

C(14)-C(1)-C(2)	113.8(2)	C(6)-C(9)-C(10)	112.8(2)
C(3)-C(2)-C(1)	113.4(2)	C(11)-C(10)-C(9)	113.3(2)
C(4)-C(3)-C(8)	115.1(2)	C(12)-C(11)-C(16)	117.4(2)
C(4)-C(3)-C(2)	123.9(2)	C(12)-C(11)-C(10)	120.2(2)
C(8)-C(3)-C(2)	119.8(2)	C(16)-C(11)-C(10)	121.4(2)
C(5)-C(4)-C(3)	121.6(2)	C(13)-C(12)-C(11)	120.4(2)
C(5)-C(4)-I(1)	117.91(17)	C(12)-C(13)-C(14)	121.6(2)
C(3)-C(4)-I(1)	120.37(18)	C(13)-C(14)-C(15)	115.5(2)
C(4)-C(5)-C(6)	120.2(2)	C(13)-C(14)-C(1)	119.3(2)
C(7)-C(6)-C(5)	117.2(2)	C(15)-C(14)-C(1)	123.9(2)
C(7)-C(6)-C(9)	121.6(2)	C(16)-C(15)-C(14)	121.4(2)
C(5)-C(6)-C(9)	120.1(2)	C(16)-C(15)-I(2)	117.54(17)
C(8)-C(7)-C(6)	120.0(2)	C(14)-C(15)-I(2)	121.07(17)
C(7)-C(8)-C(3)	122.0(2)	C(15)-C(16)-C(11)	119.9(2)

5.4: 4,12-Bis(chlorocarbonyl)[2.2]paracyclophane (84)



Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 8.4581 (8) Å	α= 90°
	b = 11.5213 (11) Å	β= 99.890 (4)°
	c = 7.5417 (6) Å	γ = 90°
Volume, Z	724.00 (11) $Å^3$, 2	

Bond lengths [Å]

C(1)-C(6)#1	1.5111(14)	C(4)-C(9)	1.4788(14)
C(1)-C(2)	1.5939(15)	C(5)-C(6)	1.3967(14)
C(2)-C(3)	1.5111(15)	C(6)-C(7)	1.3998(15)
C(3)-C(8)	1.3985(14)	C(7)-C(8)	1.3896(15)
C(3)-C(4)	1.4131(15)	C(9)-O	1.1837(15)
C(4)-C(5)	1.4046(14)	C(9)-Cl	1.8111(12)

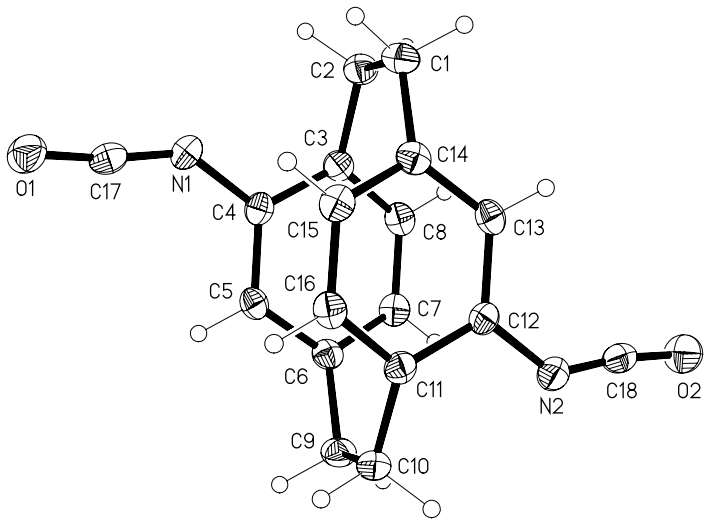
Bond angles [°]

C(6)#1-C(1)-C(2)	112.20(8)	C(3)-C(2)-C(1)	112.12(8)

C(8)-C(3)-C(4)	115.84(9)	C(5)-C(6)-C(1)#1	122.50(9)
C(8)-C(3)-C(2)	117.82(10)	C(7)-C(6)-C(1)#1	119.61(9)
C(4)-C(3)-C(2)	125.46(9)	C(8)-C(7)-C(6)	120.72(9)
C(5)-C(4)-C(3)	120.74(9)	C(7)-C(8)-C(3)	121.48(10)
C(5)-C(4)-C(9)	119.94(10)	O-C(9)-C(4)	128.35(11)
C(3)-C(4)-C(9)	118.80(9)	O-C(9)-Cl	117.89(9)
C(6)-C(5)-C(4)	120.47(10)	C(4)-C(9)-Cl	113.75(8)
C(5)-C(6)-C(7)	116.91(9)		

Symmetry transformations used to generate equivalent atoms: #1 -x,-y,-z

5.5: 4,12-Diisocyanato[2.2]paracyclophane (23)



Crystal system	Orthorhombic	
Space group	$P2_12_12_1$	
Unit cell dimensions	a = 7.2803 (8) Å	α= 90°
	b = 11.4247 (12) Å	β= 90°
	c = 16.2522 (16) Å	γ = 90°
Volume, Z	1351.8 (2) $Å^3$, 4	

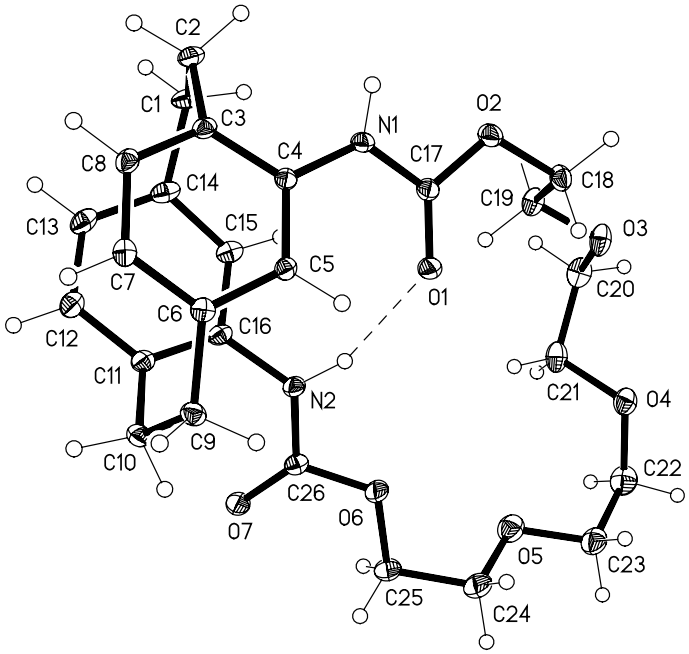
Bond lengths [Å]

C(1)-C(14)	1.512(3)	C(10)-C(11)	1.507(2)
C(1)-C(2)	1.599(3)	C(11)-C(12)	1.398(3)
C(2)-C(3)	1.512(3)	C(11)-C(16)	1.403(2)
C(3)-C(8)	1.393(2)	C(12)-C(13)	1.392(3)
C(3)-C(4)	1.403(3)	C(12)-N(2)	1.419(2)
C(4)-C(5)	1.392(2)	C(13)-C(14)	1.395(3)
C(4)-N(1)	1.408(2)	C(14)-C(15)	1.396(3)
C(5)-C(6)	1.389(2)	C(15)-C(16)	1.395(2)
C(6)-C(7)	1.394(3)	C(17)-O(1)	1.173(2)
C(6)-C(9)	1.513(3)	C(17)-N(1)	1.194(3)
C(7)-C(8)	1.394(3)	C(18)-O(2)	1.174(2)
C(9)-C(10)	1.594(3)	C(18)-N(2)	1.192(3)

Bond angles [°]

C(14)-C(1)-C(2)	112.16(15)	C(12)-C(11)-C(16)	116.18(16)
C(3)-C(2)-C(1)	112.56(15)	C(12)-C(11)-C(10)	120.87(16)
C(8)-C(3)-C(4)	116.56(16)	C(16)-C(11)-C(10)	121.50(17)
C(8)-C(3)-C(2)	121.98(17)	C(13)-C(12)-C(11)	121.47(16)
C(4)-C(3)-C(2)	120.17(16)	C(13)-C(12)-N(2)	120.36(17)
C(5)-C(4)-C(3)	120.91(16)	C(11)-C(12)-N(2)	117.62(15)
C(5)-C(4)-N(1)	121.00(17)	C(12)-C(13)-C(14)	120.38(18)
C(3)-C(4)-N(1)	117.52(16)	C(13)-C(14)-C(15)	117.54(17)
C(6)-C(5)-C(4)	120.46(17)	C(13)-C(14)-C(1)	119.66(18)
C(5)-C(6)-C(7)	117.73(16)	C(15)-C(14)-C(1)	121.64(17)
C(5)-C(6)-C(9)	119.22(17)	C(16)-C(15)-C(14)	120.23(17)
C(7)-C(6)-C(9)	121.81(16)	C(15)-C(16)-C(11)	121.32(17)
C(6)-C(7)-C(8)	120.18(16)	O(1)-C(17)-N(1)	172.6(2)
C(3)-C(8)-C(7)	121.27(17)	O(2)-C(18)-N(2)	172.5(2)
C(6)-C(9)-C(10)	112.48(14)	C(17)-N(1)-C(4)	140.05(18)
C(11)-C(10)-C(9)	112.58(15)	C(18)-N(2)-C(12)	136.85(17)

5.6: *Pseudo-ortho*-crownophane (74)



Crystal system	Orthorhombic	
Space group	$P2_12_12_1$	
Unit cell dimensions	a = 8.7908 (12) Å	α= 90°
	b = 10.6063 (14) Å	β= 90°
	c = 25.502 (4) Å	γ = 90°
Volume, Z	2377.7 (6) $Å^3$, 4	

Bond lengths [Å]

O(1)-C(17)	1.214(2)	O(5)-C(23)	1.409(3)
O(2)-C(17)	1.339(2)	O(5)-C(24)	1.413(3)
O(2)-C(18)	1.444(2)	O(6)-C(26)	1.349(2)
O(3)-C(19)	1.411(2)	O(6)-C(25)	1.438(2)
O(3)-C(20)	1.423(2)	O(7)-C(26)	1.204(2)
O(4)-C(21)	1.419(2)	N(1)-C(17)	1.348(2)
O(4)-C(22)	1.422(3)	N(1)-C(4)	1.416(2)

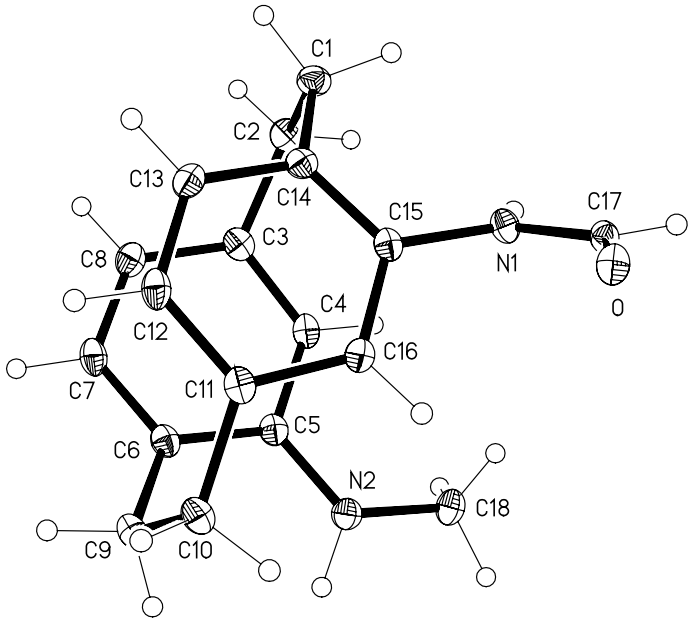
N(2)-C(26)	1.348(2)	C(9)-C(10)	1.575(2)
N(2)-C(16)	1.414(2)	C(10)-C(11)	1.507(2)
C(1)-C(14)	1.509(3)	C(11)-C(12)	1.395(2)
C(1)-C(2)	1.583(3)	C(11)-C(16)	1.396(2)
C(2)-C(3)	1.509(2)	C(12)-C(13)	1.379(3)
C(3)-C(8)	1.384(2)	C(13)-C(14)	1.381(3)
C(3)-C(4)	1.395(2)	C(14)-C(15)	1.388(2)
C(4)-C(5)	1.388(2)	C(15)-C(16)	1.390(2)
C(5)-C(6)	1.382(2)	C(18)-C(19)	1.508(3)
C(6)-C(7)	1.382(2)	C(20)-C(21)	1.498(3)
C(6)-C(9)	1.504(2)	C(22)-C(23)	1.487(3)
C(7)-C(8)	1.380(3)	C(24)-C(25)	1.486(3)

Bond angles [°]

C(17)-O(2)-C(18)	114.64(14)	C(8)-C(7)-C(6)	119.38(16)
C(19)-O(3)-C(20)	112.42(14)	C(7)-C(8)-C(3)	121.68(16)
C(21)-O(4)-C(22)	115.67(16)	C(6)-C(9)-C(10)	111.60(14)
C(23)-O(5)-C(24)	111.49(17)	C(11)-C(10)-C(9)	113.00(14)
C(26)-O(6)-C(25)	115.27(15)	C(12)-C(11)-C(16)	116.06(16)
C(17)-N(1)-C(4)	125.68(14)	C(12)-C(11)-C(10)	119.58(16)
C(26)-N(2)-C(16)	124.38(15)	C(16)-C(11)-C(10)	122.50(15)
C(14)-C(1)-C(2)	112.08(15)	C(13)-C(12)-C(11)	121.66(17)
C(3)-C(2)-C(1)	112.03(14)	C(12)-C(13)-C(14)	120.35(17)
C(8)-C(3)-C(4)	116.97(15)	C(13)-C(14)-C(15)	117.31(17)
C(8)-C(3)-C(2)	119.39(15)	C(13)-C(14)-C(1)	122.04(17)
C(4)-C(3)-C(2)	122.14(15)	C(15)-C(14)-C(1)	119.26(18)
C(5)-C(4)-C(3)	120.11(15)	C(14)-C(15)-C(16)	120.84(18)
C(5)-C(4)-N(1)	121.66(15)	C(15)-C(16)-C(11)	120.48(16)
C(3)-C(4)-N(1)	117.83(15)	C(15)-C(16)-N(2)	117.02(16)
C(6)-C(5)-C(4)	120.31(15)	C(11)-C(16)-N(2)	121.46(15)
C(5)-C(6)-C(7)	118.42(15)	O(1)-C(17)-O(2)	123.41(15)
C(5)-C(6)-C(9)	118.65(15)	O(1)-C(17)-N(1)	126.82(16)
C(7)-C(6)-C(9)	121.64(15)	O(2)-C(17)-N(1)	109.77(14)

O(2)-C(18)-C(19)	110.34(15)	O(5)-C(24)-C(25)	109.92(18)
O(3)-C(19)-C(18)	106.30(15)	O(6)-C(25)-C(24)	107.71(17)
O(3)-C(20)-C(21)	112.85(16)	O(7)-C(26)-N(2)	127.08(17)
O(4)-C(21)-C(20)	107.71(16)	O(7)-C(26)-O(6)	123.90(16)
O(4)-C(22)-C(23)	114.87(16)	N(2)-C(26)-O(6)	109.02(15)
O(5)-C(23)-C(22)	109.99(18)		

5.7: *Pseudo-ortho*-(*N*-formyl)(*N′*-methyl)diamino[2.2]paracyclophane (79)



Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 13.158 (2) Å	α= 90°
	b = 8.1464 (14) Å	β= 116.039 (6)°
	c = 14.985 (3) Å	γ = 90°
Volume, Z	1443.3 (4) $Å^3$, 4	

Bond lengths [Å]

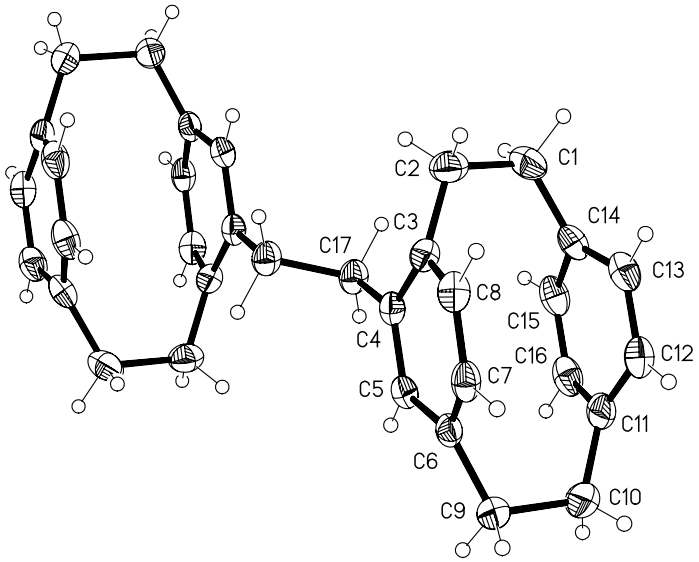
O-C(17)	1.2310(18)	N(1)-C(15)	1.4377(19)
N(1)-C(17)	1.3416(19)	N(2)-C(5)	1.382(2)

N(2)-C(18)	1.446(2)	C(7)-C(8)	1.393(2)
C(1)-C(14)	1.516(2)	C(9)-C(10)	1.582(2)
C(1)-C(2)	1.595(2)	C(10)-C(11)	1.512(2)
C(2)-C(3)	1.515(2)	C(11)-C(16)	1.393(2)
C(3)-C(8)	1.394(2)	C(11)-C(12)	1.399(2)
C(3)-C(4)	1.396(2)	C(12)-C(13)	1.379(2)
C(4)-C(5)	1.403(2)	C(13)-C(14)	1.403(2)
C(5)-C(6)	1.420(2)	C(14)-C(15)	1.398(2)
C(6)-C(7)	1.389(2)	C(15)-C(16)	1.393(2)
C(6)-C(9)	1.522(2)		

Bond angles [°]

C(17)-N(1)-C(15)	123.12(13)	C(6)-C(9)-C(10)	112.27(12)
C(5)-N(2)-C(18)	121.51(14)	C(11)-C(10)-C(9)	111.76(12)
C(14)-C(1)-C(2)	113.24(12)	C(16)-C(11)-C(12)	116.82(14)
C(3)-C(2)-C(1)	112.32(12)	C(16)-C(11)-C(10)	120.45(14)
C(8)-C(3)-C(4)	118.25(14)	C(12)-C(11)-C(10)	121.20(14)
C(8)-C(3)-C(2)	121.65(15)	C(13)-C(12)-C(11)	120.49(14)
C(4)-C(3)-C(2)	118.65(14)	C(12)-C(13)-C(14)	121.60(14)
C(3)-C(4)-C(5)	121.41(14)	C(15)-C(14)-C(13)	116.09(14)
N(2)-C(5)-C(4)	121.19(14)	C(15)-C(14)-C(1)	123.57(14)
N(2)-C(5)-C(6)	119.56(14)	C(13)-C(14)-C(1)	119.12(14)
C(4)-C(5)-C(6)	118.62(14)	C(16)-C(15)-C(14)	120.73(13)
C(7)-C(6)-C(5)	117.70(15)	C(16)-C(15)-N(1)	118.25(13)
C(7)-C(6)-C(9)	119.92(14)	C(14)-C(15)-N(1)	120.58(13)
C(5)-C(6)-C(9)	120.76(14)	C(15)-C(16)-C(11)	120.96(14)
C(6)-C(7)-C(8)	121.94(15)	O-C(17)-N(1)	125.88(14)
C(7)-C(8)-C(3)	119.36(15)		

5.8: (*trans, meso*)1,2-Bis-(4-[2.2]paracyclophanyl)ethane (140)



Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 14.239 (2) Å	α= 90°
	b = 7.6424 (11) Å	β= 106.724 (5)°
	c = 11.6050 (16) Å	γ = 90°
Volume, Z	1209.5 (3) $Å^3$, 2	

Bond lengths [Å]

C(1)-C(14)	1.509(3)	C(6)-C(9)	1.512(2)
C(1)-C(2)	1.587(3)	C(7)-C(8)	1.385(2)
C(2)-C(3)	1.513(2)	C(9)-C(10)	1.572(3)
C(3)-C(8)	1.402(2)	C(10)-C(11)	1.515(3)
C(3)-C(4)	1.412(2)	C(11)-C(12)	1.393(2)
C(4)-C(5)	1.389(2)	C(11)-C(16)	1.399(3)
C(4)-C(17)	1.510(2)	C(12)-C(13)	1.384(3)
C(5)-C(6)	1.396(2)	C(13)-C(14)	1.396(2)
C(6)-C(7)	1.389(2)	C(14)-C(15)	1.401(2)

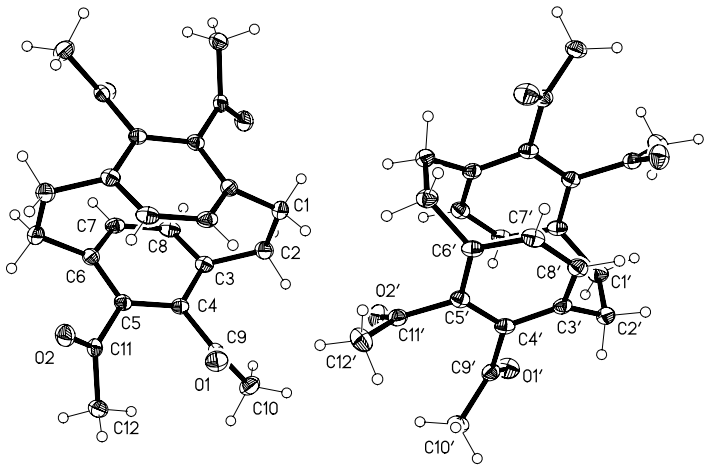
C(15)-C(16)	1.387(3)	C(17)-C(17)#1	1.529(3)

Bond angles [°]

C(14)-C(1)-C(2)	112.76(14)	C(6)-C(9)-C(10)	112.75(14)
C(3)-C(2)-C(1)	113.07(14)	C(11)-C(10)-C(9)	113.87(14)
C(8)-C(3)-C(4)	117.33(14)	C(12)-C(11)-C(16)	116.88(16)
C(8)-C(3)-C(2)	118.89(14)	C(12)-C(11)-C(10)	120.67(18)
C(4)-C(3)-C(2)	122.23(14)	C(16)-C(11)-C(10)	121.02(17)
C(5)-C(4)-C(3)	118.88(13)	C(13)-C(12)-C(11)	120.91(16)
C(5)-C(4)-C(17)	118.94(13)	C(12)-C(13)-C(14)	120.88(15)
C(3)-C(4)-C(17)	121.96(14)	C(13)-C(14)-C(15)	116.64(16)
C(4)-C(5)-C(6)	122.02(14)	C(13)-C(14)-C(1)	121.22(16)
C(7)-C(6)-C(5)	117.24(14)	C(15)-C(14)-C(1)	120.89(16)
C(7)-C(6)-C(9)	121.58(14)	C(16)-C(15)-C(14)	120.82(16)
C(5)-C(6)-C(9)	119.97(15)	C(15)-C(16)-C(11)	120.56(15)
C(8)-C(7)-C(6)	120.21(13)	C(4)-C(17)-C(17)#1	111.70(16)
C(7)-C(8)-C(3)	121.28(14)		

Symmetry transformations used to generate equivalent atoms: #1 -x+1,-y+1,-z+1

5.9: 4,5,12,13-Tetraacetyl[2.2]paracyclophane (30)



Crystal system Monoclinic

Space group	$P2_1/c$	
Unit cell dimensions	a = 8.0251 (8) Å	α= 90°
	b = 14.8898 (14) Å	β= 93.163 (4)°
	c = 15.5679 (16) Å	γ = 90°
Volume, Z	1857.4(3) $Å^3$, 4	

Bond lengths [Å]

C(1)-C(6)#1	1.5089(19)	C(1')-C(6')#2	1.5165(18)
C(1)-C(2)	1.589(2)	C(1')-C(2')	1.5881(18)
C(2)-C(3)	1.5108(19)	C(2')-C(3')	1.5121(19)
C(3)-C(8)	1.3927(18)	C(3')-C(8')	1.3928(19)
C(3)-C(4)	1.4066(18)	C(3')-C(4')	1.4070(19)
C(4)-C(5)	1.4063(18)	C(4')-C(5')	1.4120(19)
C(4)-C(9)	1.5077(18)	C(4')-C(9')	1.5059(19)
C(5)-C(6)	1.4106(18)	C(5')-C(6')	1.4087(19)
C(5)-C(11)	1.5050(18)	C(5')-C(11')	1.5078(19)
C(6)-C(7)	1.3982(19)	C(6')-C(7')	1.3958(19)
C(7)-C(8)	1.381(2)	C(7')-C(8')	1.3890(19)
C(9)-O(1)	1.2144(16)	C(9')-O(1')	1.2194(16)
C(9)-C(10)	1.5029(19)	C(9')-C(10')	1.5069(19)
C(11)-O(2)	1.2208(16)	C(11')-O(2')	1.2150(16)
C(11)-C(12)	1.5055(19)	C(11')-C(12')	1.5024(19)

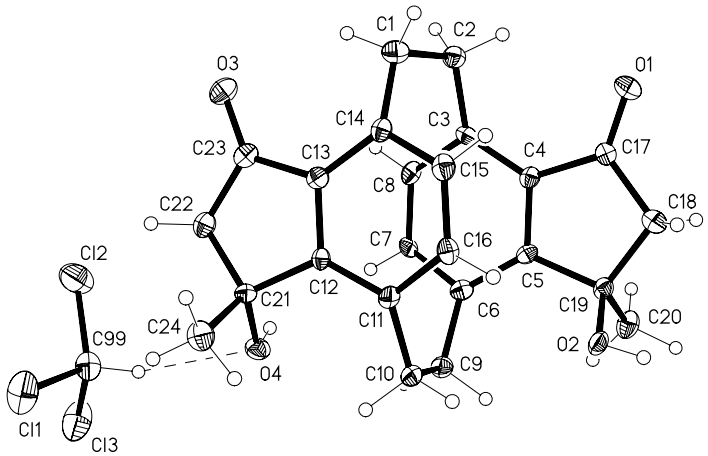
Bond angles [°]

C(6)#1-C(1)-C(2)	112.99(11)	C(4)-C(5)-C(6)	120.13(12)
C(3)-C(2)-C(1)	112.50(11)	C(4)-C(5)-C(11)	120.29(11)
C(8)-C(3)-C(4)	117.07(12)	C(6)-C(5)-C(11)	119.54(12)
C(8)-C(3)-C(2)	118.88(12)	C(7)-C(6)-C(5)	116.80(12)
C(4)-C(3)-C(2)	122.55(12)	C(7)-C(6)-C(1)#1	118.06(12)
C(5)-C(4)-C(3)	120.18(12)	C(5)-C(6)-C(1)#1	124.49(12)
C(5)-C(4)-C(9)	118.97(11)	C(8)-C(7)-C(6)	121.09(12)
C(3)-C(4)-C(9)	119.97(12)	C(7)-C(8)-C(3)	121.06(12)

O(1)-C(9)-C(10)	121.38(12)	C(6')-C(5')-C(4')	120.08(12)
O(1)-C(9)-C(4)	120.12(12)	C(6')-C(5')-C(11')	119.37(12)
C(10)-C(9)-C(4)	118.44(12)	C(4')-C(5')-C(11')	120.13(12)
O(2)-C(11)-C(5)	121.01(12)	C(7')-C(6')-C(5')	117.13(12)
O(2)-C(11)-C(12)	121.04(12)	C(7')-C(6')-C(1')#2	118.45(12)
C(5)-C(11)-C(12)	117.74(12)	C(5')-C(6')-C(1')#2	122.76(12)
C(6')#2-C(1')-C(2')	112.11(11)	C(8')-C(7')-C(6')	120.76(13)
C(3')-C(2')-C(1')	113.56(11)	C(7')-C(8')-C(3')	120.92(13)
C(8')-C(3')-C(4')	117.43(12)	O(1')-C(9')-C(4')	120.23(12)
C(8')-C(3')-C(2')	117.82(12)	O(1')-C(9')-C(10')	120.29(13)
C(4')-C(3')-C(2')	124.25(13)	C(4')-C(9')-C(10')	119.40(12)
C(3')-C(4')-C(5')	119.85(12)	O(2')-C(11')-C(12')	121.82(13)
C(3')-C(4')-C(9')	119.50(12)	O(2')-C(11')-C(5')	120.93(12)
C(5')-C(4')-C(9')	120.55(12)	C(12')-C(11')-C(5')	117.19(12)

Symmetry transformations used to generate equivalent atoms: #1 -x,-y+1,-z #2 -x+1,-y,-z

5.10: *syn*-19,21-Dihydroxy-19,21-dimethyl[2.2]indanonophane-17,23-dione (34)



Crystal system	Orthorhombic	
Space group	$Pca2_1$	
Unit cell dimensions	a = 19.286 (3) Å	α= 90°
	b = 12.253 (2) Å	β= 90°

	c = 9.527 (2) Å		γ = 90°
Volume, Z	2251.2(7) Å^3, 4		

Bond lengths [Å]

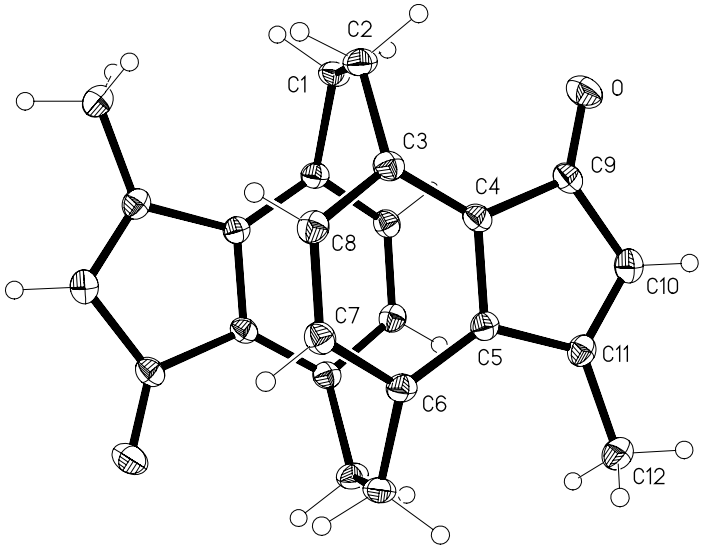
C(1)-C(14)	1.521(11)	C(13)-C(14)	1.415(11)
C(1)-C(2)	1.573(11)	C(13)-C(23)	1.464(11)
C(2)-C(3)	1.525(11)	C(14)-C(15)	1.398(11)
C(3)-C(8)	1.380(11)	C(15)-C(16)	1.403(12)
C(3)-C(4)	1.413(11)	C(17)-O(1)	1.243(9)
C(4)-C(5)	1.403(11)	C(17)-C(18)	1.494(12)
C(4)-C(17)	1.472(10)	C(18)-C(19)	1.535(11)
C(5)-C(6)	1.399(10)	C(19)-O(2)	1.417(9)
C(5)-C(19)	1.526(11)	C(19)-C(20)	1.528(11)
C(6)-C(7)	1.393(11)	C(21)-O(4)	1.432(10)
C(6)-C(9)	1.512(11)	C(21)-C(22)	1.532(12)
C(7)-C(8)	1.407(11)	C(21)-C(24)	1.535(11)
C(9)-C(10)	1.579(11)	C(22)-C(23)	1.497(11)
C(10)-C(11)	1.523(11)	C(23)-O(3)	1.247(9)
C(11)-C(12)	1.395(10)	C(99)-Cl(2)	1.758(10)
C(11)-C(16)	1.405(11)	C(99)-Cl(3)	1.762(9)
C(12)-C(13)	1.406(11)	C(99)-Cl(1)	1.773(8)
C(12)-C(21)	1.542(11)		

Bond angles [°]

C(14)-C(1)-C(2)	112.8(7)	C(6)-C(5)-C(4)	120.9(7)
C(3)-C(2)-C(1)	112.1(6)	C(6)-C(5)-C(19)	127.5(7)
C(8)-C(3)-C(4)	114.8(8)	C(4)-C(5)-C(19)	111.6(7)
C(8)-C(3)-C(2)	119.9(8)	C(7)-C(6)-C(5)	115.3(7)
C(4)-C(3)-C(2)	124.3(7)	C(7)-C(6)-C(9)	118.4(7)
C(5)-C(4)-C(3)	121.7(7)	C(5)-C(6)-C(9)	125.2(8)
C(5)-C(4)-C(17)	108.3(7)	C(6)-C(7)-C(8)	121.9(7)
C(3)-C(4)-C(17)	129.6(8)	C(3)-C(8)-C(7)	121.4(8)

C(6)-C(9)-C(10)	113.0(7)	O(2)-C(19)-C(5)	107.9(6)
C(11)-C(10)-C(9)	112.1(7)	O(2)-C(19)-C(20)	110.3(7)
C(12)-C(11)-C(16)	116.2(7)	C(5)-C(19)-C(20)	110.3(7)
C(12)-C(11)-C(10)	123.5(7)	O(2)-C(19)-C(18)	113.1(7)
C(16)-C(11)-C(10)	118.8(7)	C(5)-C(19)-C(18)	103.7(6)
C(11)-C(12)-C(13)	120.5(7)	C(20)-C(19)-C(18)	111.3(6)
C(11)-C(12)-C(21)	128.7(7)	O(4)-C(21)-C(22)	112.9(7)
C(13)-C(12)-C(21)	110.8(7)	O(4)-C(21)-C(24)	105.0(7)
C(12)-C(13)-C(14)	122.1(8)	C(22)-C(21)-C(24)	113.5(7)
C(12)-C(13)-C(23)	109.3(7)	O(4)-C(21)-C(12)	114.0(6)
C(14)-C(13)-C(23)	128.4(8)	C(22)-C(21)-C(12)	103.1(7)
C(15)-C(14)-C(13)	115.1(8)	C(24)-C(21)-C(12)	108.4(7)
C(15)-C(14)-C(1)	119.3(7)	C(23)-C(22)-C(21)	107.3(7)
C(13)-C(14)-C(1)	124.2(8)	O(3)-C(23)-C(13)	128.2(8)
C(14)-C(15)-C(16)	121.4(8)	O(3)-C(23)-C(22)	123.3(7)
C(15)-C(16)-C(11)	121.5(8)	C(13)-C(23)-C(22)	108.5(7)
O(1)-C(17)-C(4)	125.2(8)	Cl(2)-C(99)-Cl(3)	110.7(5)
O(1)-C(17)-C(18)	125.5(7)	Cl(2)-C(99)-Cl(1)	110.6(5)
C(4)-C(17)-C(18)	109.3(7)	Cl(3)-C(99)-Cl(1)	109.1(5)
C(17)-C(18)-C(19)	106.7(6)		

5.11: *anti*-19,23-Dimethyl[2.2]indenonophane-17,21-dione (135)



Crystal system	Monoclinic	
Space group	C2/c	
Unit cell dimensions	a = 14.051 (2) Å	α= 90°
	b = 8.0225 (12) Å	β= 96.695 (6)°
	c = 14.536 (2) Å	γ = 90°
Volume, Z	1627.5(4) Å^3, 4	

Bond lengths [Å]

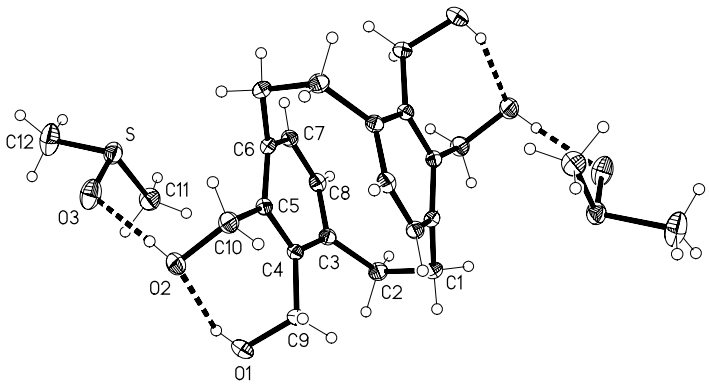
O-C(9)	1.2212(15)	C(5)-C(6)	1.3912(16)
C(1)-C(6)#1	1.5150(15)	C(5)-C(11)	1.4990(16)
C(1)-C(2)	1.5891(17)	C(6)-C(7)	1.4183(16)
C(2)-C(3)	1.5119(16)	C(7)-C(8)	1.3862(16)
C(3)-C(4)	1.3868(16)	C(9)-C(10)	1.4844(18)
C(3)-C(8)	1.4114(16)	C(10)-C(11)	1.3519(17)
C(4)-C(5)	1.4157(15)	C(11)-C(12)	1.4940(17)
C(4)-C(9)	1.5005(16)		

Bond angles [°]

C(6)#1-C(1)-C(2)	112.89(9)	C(5)-C(6)-C(1)#1	124.95(10)
C(3)-C(2)-C(1)	111.75(9)	C(7)-C(6)-C(1)#1	118.45(10)
C(4)-C(3)-C(8)	115.29(10)	C(8)-C(7)-C(6)	122.17(10)
C(4)-C(3)-C(2)	123.28(10)	C(7)-C(8)-C(3)	120.60(11)
C(8)-C(3)-C(2)	120.39(10)	O-C(9)-C(10)	127.22(11)
C(3)-C(4)-C(5)	122.59(10)	O-C(9)-C(4)	126.83(11)
C(3)-C(4)-C(9)	129.67(10)	C(10)-C(9)-C(4)	105.94(10)
C(5)-C(4)-C(9)	107.14(10)	C(11)-C(10)-C(9)	109.47(11)
C(6)-C(5)-C(4)	120.06(10)	C(10)-C(11)-C(12)	126.29(11)
C(6)-C(5)-C(11)	131.78(10)	C(10)-C(11)-C(5)	109.45(10)
C(4)-C(5)-C(11)	107.80(10)	C(12)-C(11)-C(5)	124.22(11)
C(5)-C(6)-C(7)	115.36(10)		

Symmetry transformations used to generate equivalent atoms: #1 -x+1/2,-y+1/2,-z+1

5.12: 4,5,12,13-Tetra(hydroxymethyl)[2.2]paracyclophane (98)



Crystal system	Triclinic	
Space group	P (-1)	
Unit cell dimensions	a = 7.1033 (8) Å	α= 86.779 (4)°
	b = 7.7805 (8) Å	β= 88.532 (4)°
	c = 10.9835 (12) Å	γ = 76.306 (4)°

Volume, Z	588.79(11) Å^3, 1

Bond lengths [Å]

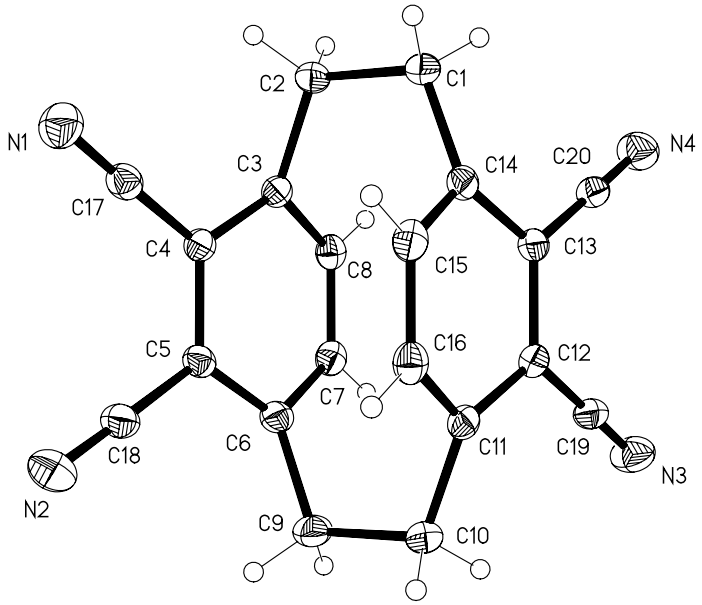
C(1)-C(6)#1	1.5173(15)	C(5)-C(10)	1.5141(15)
C(1)-C(2)	1.5893(16)	C(6)-C(7)	1.3979(15)
C(2)-C(3)	1.5178(15)	C(7)-C(8)	1.3864(15)
C(3)-C(8)	1.4008(15)	C(9)-O(1)	1.4313(14)
C(3)-C(4)	1.4055(15)	C(10)-O(2)	1.4400(14)
C(4)-C(5)	1.4095(14)	S-O(3)	1.5147(10)
C(4)-C(9)	1.5144(15)	S-C(11)	1.7822(13)
C(5)-C(6)	1.4113(14)	S-C(12)	1.7862(14)

Bond angles [°]

C(6)#1-C(1)-C(2)	112.00(9)	C(7)-C(6)-C(5)	117.26(10)
C(3)-C(2)-C(1)	112.57(9)	C(7)-C(6)-C(1)#1	119.07(9)
C(8)-C(3)-C(4)	117.44(10)	C(5)-C(6)-C(1)#1	122.40(10)
C(8)-C(3)-C(2)	118.81(10)	C(8)-C(7)-C(6)	121.09(10)
C(4)-C(3)-C(2)	122.64(10)	C(7)-C(8)-C(3)	120.46(10)
C(3)-C(4)-C(5)	120.23(9)	O(1)-C(9)-C(4)	112.18(9)
C(3)-C(4)-C(9)	119.80(9)	O(2)-C(10)-C(5)	112.08(9)
C(5)-C(4)-C(9)	119.77(10)	O(3)-S-C(11)	105.51(6)
C(4)-C(5)-C(6)	119.80(10)	O(3)-S-C(12)	105.10(6)
C(4)-C(5)-C(10)	119.95(9)	C(11)-S-C(12)	97.38(7)
C(6)-C(5)-C(10)	120.04(10)		

Symmetry transformations used to generate equivalent atoms: #1 -x+1,-y+2,-z+1

5.13: 4,5,12,13-Tetracyano[2.2]paracyclophane (96)



Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.0277 (6) Å	α= 90°
	b = 15.1197 (14) Å	β= 103.603 (4)°
	c = 14.3219 (14) Å	γ = 90°
Volume, Z	1479.1(2) $Å^3$, 4	

Bond lengths [Å]

C(1)-C(14)	1.5102(14)	C(6)-C(7)	1.3981(15)
C(1)-C(2)	1.5877(15)	C(6)-C(9)	1.5137(14)
C(2)-C(3)	1.5091(14)	C(7)-C(8)	1.3892(15)
C(3)-C(4)	1.3977(14)	C(9)-C(10)	1.5856(15)
C(3)-C(8)	1.4004(14)	C(10)-C(11)	1.5092(14)
C(4)-C(5)	1.4180(14)	C(11)-C(16)	1.4001(14)
C(4)-C(17)	1.4407(15)	C(11)-C(12)	1.4002(14)
C(5)-C(6)	1.3974(15)	C(12)-C(13)	1.4178(14)
C(5)-C(18)	1.4418(15)	C(12)-C(19)	1.4377(14)

C(13)-C(14)	1.4005(14)	C(17)-N(1)	1.1487(14)
C(13)-C(20)	1.4394(15)	C(18)-N(2)	1.1430(14)
C(14)-C(15)	1.3990(15)	C(19)-N(3)	1.1491(14)
C(15)-C(16)	1.3852(15)	C(20)-N(4)	1.1455(14)

Bond angles [°]

C(14)-C(1)-C(2)	112.60(8)	C(15)-C(14)-C(13)	116.57(9)
C(3)-C(2)-C(1)	112.28(8)	C(15)-C(14)-C(1)	120.58(9)
C(4)-C(3)-C(8)	116.84(9)	C(13)-C(14)-C(1)	121.85(10)
C(4)-C(3)-C(2)	122.22(9)	C(16)-C(15)-C(14)	121.14(10)
C(8)-C(3)-C(2)	119.90(9)	C(15)-C(16)-C(11)	121.23(10)
C(3)-C(4)-C(5)	120.30(9)	N(1)-C(17)-C(4)	178.89(12)
C(3)-C(4)-C(17)	119.76(9)	N(2)-C(18)-C(5)	179.11(13)
C(5)-C(4)-C(17)	119.41(9)	N(3)-C(19)-C(12)	179.21(12)
C(6)-C(5)-C(4)	120.76(9)	N(4)-C(20)-C(13)	178.59(11)
C(6)-C(5)-C(18)	120.58(9)		
C(4)-C(5)-C(18)	118.19(9)		
C(5)-C(6)-C(7)	116.37(9)		
C(5)-C(6)-C(9)	122.26(10)		
C(7)-C(6)-C(9)	120.25(10)		
C(8)-C(7)-C(6)	121.47(10)		
C(7)-C(8)-C(3)	120.88(10)		
C(6)-C(9)-C(10)	112.44(8)		
C(11)-C(10)-C(9)	112.41(8)		
C(16)-C(11)-C(12)	116.70(9)		
C(16)-C(11)-C(10)	120.21(9)		
C(12)-C(11)-C(10)	122.11(9)		
C(11)-C(12)-C(13)	120.25(9)		
C(11)-C(12)-C(19)	120.20(9)		
C(13)-C(12)-C(19)	119.01(9)		
C(14)-C(13)-C(12)	120.53(9)		
C(14)-C(13)-C(20)	119.90(9)		
C(12)-C(13)-C(20)	119.22(9)		

References

[1] D. J. Cram, H. Steinberg, *J. Am. Chem. Soc*., **1951**, *73*, 5691–5704.

[2] H. Hopf, *Classics in Hydrocarbon Chemistry*, Wiley-VCH, Weinheim, **2000**, Chapter 12.3, 337.

[3] H. Wieland, D. Juchum, J. Maier, *Ber. Dt. Chem. Ges.*, **1931**, *64B*, 2513–2516.

[4] A. Lüttringhaus, *Liebigs Ann. Chem*., **1937**, *528*, 181–210.

[5] W. M. Schubert, W. A. Sweeney, H. K. Latourette, *J. Am. Chem. Soc.*, **1954**, *76*, 5462–5466.

[6] D. J. Cram, J. Abell, *J. Am. Chem. Soc.*, **1955**, *77*, 1179–1186.

[7] International Union of Pure and Applied Chemistry, Division of Organic Chemistry, Commission on Nomenclature of Organic Chemistry. "Phane Nomenclature, Part I: Phane Parent Names". *Pure Appl. Chem*. **1998**, *70*, 1513–1545.

[8] H. J. Reich, D. J. Cram, *J. Am. Chem. Soc*., **1969**, *91*, 3505–3516.

[9] H. Hopf, S. Trampe, K. Menke, *Chem. Ber*., **1977**, *110*, 371–372.

[10] H. Hopf, *Angew. Chem*., **2003**, *115*, 2928–2931; *Angew. Chem. Int. Ed*., **2003**, *42*, 2822–2825.

[11] K. El Shaieb, Vijay Narayanan, H. Hopf, I. Dix, A. Fischer, P. G. Jones, L. Ernst, K. Ibrom, *Eur. J. Org. Chem*., **2003**, 567–577.

[12] V. Rozenberg, Y. Belokon, M. Moscalenko, N. Ikonnikov, L. Yashkina, D. Antonov, E. Vorontsov, *Tetrahedron Asym*., **1997**, *8*, 3245–3250.

[13] S. Tanji, A. Ohno, I. Sato, K. Soai, *Organic Letters*, **2001**, *3*, 287–289.

[14] A. Gerosa, C. Malan, D. Herzberg, *Organic Letters*, **2001**, *3*, 3687–3690.

[15] J. Lahann, D. Klee, H. Höcker, *Macromol. Rapid Commun*., **1998**, *19*, 441–444.

[16] H. Höcker, J. Lahann, D. Klee, H. Thelen, D. Vorwerk, *J. Materials Sci.:Materials in Medicine*, **1999**, *10*, 443–448.

[17] L. Ernst, K. Ibrom, *Magn. Reson. Chem*., **1997**, *35*, 868–876.

[18] S. Sankararaman, H. Hopf, I. Dix, P.G. Jones, *Eur. J. Org. Chem*., **2000**, 2699–2701.

[19] P. Comba, A. Fath, G. Huttner, L. Zsolnai, *J. Chem. Soc. Chem. Comm*., **1996**, *16*, 1885–1886.

[20] H. Zitt, H. Hopf, I. Dix, P. G. Jones, *Eur. J. Org. Chem.*, **2001**, 2298–2307.

[21] D. J. Cram, N. L. Allinger, *J. Am. Chem. Soc*., **1955**, *77*, 6289–6292.

[22] H. Hopf, W. Grahn, D. G. Barrett, A. Gerdes, J. Hilmer, J. Hucker, Y. Okamoto, Y. Kaida, *Chem. Ber*., **1990**, *123*, 841–845.

[23] P. S. Engel, *Chem. Rev*., **1980**, *80*, 99–150.

[24] V. I. Rozenberg, D. Yu. Antonov, E. V. Sergeeva, E. V. Voronstsov, *Russ. Chem. Bulletin*, **1997**, *46*, 1897–1900.

[25] P. J. Pye, K. Rossen, R. A. Reamer, N. N. Tsou, R. P. Volante, P. J. Reider, *J. Am. Chem. Soc*., **1997**, *119*, 6207–6208.

[26] B. S. Bal, Jr W. E. Childers, H. W. Pinnick, *Tetrahedron*, **1981**, *37*, 2091–2094.

[27] R. Meissner, X. Garcias, S. Mecozzi, J. Rebek, Jr., *J. Am. Chem. Soc.*, **1997**, *119*, 77–85.

[28] H. Zitt, Dissertation, Univ. of Braunschweig, **1999**.

[29] C. J. Pedersen, *J. Am. Chem. Soc*., **1967**, *89*, 2495–2496.

[30] J. D. Lamb, R. M. Izatt, J. J. Christensen, *Coordination chemistry of Macrocyclic compounds*, Plenum press, New York, **1979**, 145–218.

[31] R. M. Kellogg, F. Vögtle, *Topics in Current Chemistry*, Springer-Verlag, New York, **1982**.

[32] Y. L. Yeh, W. F. Gorham, *J. Org. Chem*., **1969**, *34*, 2366–2370.

[33] S. Hentschel, Dissertation, Univ. of Braunschweig, **1989**.

[34] H. C. Brown, E. F. Knights, C. G. Scouten, *J. Am. Chem. Soc*., **1974**, *96*, 7765–7770.

[35] A. Alexakis, A. Tomassini, C. Chouillet, S. Roland, P. Mangeney, G. Bernardinelli, *Angew. Chem*., **2000**, *112*, 4259–4261; *Angew. Chem. Int. Ed*., **2000**, *39*, 4093–4095.

[36] H. Hopf, I. Böhm, J. Kleinschroth, *Org. Synth*., **1981**, *60*, 41–48.

[37] H. Hopf, F. Th. Lenich, *Chem. Ber*., **1974**, *107*, 1891–1902.

[38] J. Lugtenburg, A. A. C. van Wijk, M. B. van de Weerd, *Eur. J. Org. Chem*., **2003**, 863–868.

[39] V. Boekelheide, J. E. Garbe, *J. Am. Chem. Soc*., **1983**, *105*, 7384–7388.

[40] E. H. Eltamany, Dissertation, Univ. of Braunschweig, **1983**.

[41] M. P. Cava, A. F. C. Hsu, *J. Am. Chem. Soc*., **1972**, *94*, 6441–6444.

[42] G. P. Bartholomew, G. C. Bazan, *J. Am. Chem. Soc*., **2002**, *124*, 5183–5196.

[43] P. J. Dunn, C. W. Rees, *J. Chem. Soc. Perkin Trans I*, **1987**, *7*, 1579–1584.

[44] C. M. Wong, T. L. Ho, *Synthetic Comm*., **1974**, *4*, 25–27.

[45] E. Negishi, A. O. King, W. L. Klima, *J. Org. Chem*., **1980**, *45*, 2526–2528.

[46] A. Stanger, N. B. Mergui, S. Perl, *Eur. J. Org. Chem*., **2003**, 2709–2712.

[47] S. Takahashi, N. Mori, *J. Chem. Soc. Perkin Trans I*, **1991**, 2029–2032.

[48] F. Mitzel, S. FitzGerald, R. Faust, *Chem. Eur. J*., **2003**, *9*, 1233–1241.

[49] A. A Aly, *Spectrochimia Acta Part A*, **1999**, *55*, 79–88.

[50] E. D. Matveeve, D. B. Feshin, N. S. Zefirov, *Russ. J. Org. Chem.*, **2001**, *37*, 52–55.

[51] K. Watanabe, K. Hata, M. Sato, T. Ito, I. Motoyama, *Bull. Chem. Soc. Japan*, **1969**, *42*, 1976–1981.

[52] F. Kienzle, E. C. Taylor, *J. Org. Chem.*, **1970**, *2*, 528–529.

[53] J. Hillmer, Dissertation, Univ. of Braunschweig, **1991**.

[54] E. L. Popova, V. I. Rozenberg, Z. A. Starikova, S. K. Baumann, H. S. Kitzerow, H. Hopf, *Angew. Chem.*, **2002**, *114*, 3561–3564; *Angew. Chem. Int. Ed.*, **2002**, *41*, 3411–3414.

[55] R. A. Gedu, B. Rigo, *Tetrahedron Lett.*, **2004**, *45*, 1829–1832.

[56] H. A. Staab, U. E. Meissner, B. Meissner, *Chem. Ber.*, **1976**, *109*, 3875–3885.

[57] A. Buquet, A. Couture, A. L. Combier, *J. Org. Chem.*, **1979**, *44*, 2300–2303.

[58] K. H. Wong, H. L. Ng, *J. Coord. Chem.*, **1981**, *11*, 49–55.

[59] T. Laue, Dissertation, Univ. of Braunschweig, **1991**.

[60] R. C. Joines, A. B. Turner, W. M. Jones, *J. Am. Chem. Soc.*, **1969**, *91*, 7754–7755.

[61] H. Hopf, R. Gleiter, *Modern Cyclophane Chemistry*, Wiley-VCH, Weinheim, **2004**, Chapter 17, 435–462.

[62] L. Bondarenko, I. Dix, H. Hinrichs, H. Hopf, *Synthesis*, **2004**, *16*, 2751–2759.

[63] E. S. Baker, J. W. Hong, J. Gidden, G. P. Bartholomew, G. C. Bazan, M. T. Bowers, *J. Am. Chem. Soc.*, **2004**, *126*, 6255–6257.

[64] K. Y. Suh, R. Langer, J. Lahann, *Adv. Mater.*, **2004**, *16*, 1401–1405.

[65] P. J. Stang, F. Diederich, *Modern Acetylene Chemistry*, Wiley-VCH, Weinheim, **1995**, 34–35.

[66] A. A. Aly, H. Hopf, L. Ernst, *Eur. J. Org. Chem.*, **2000**, *17*, 3021–3030.

[67] J. Grunenberg, R. Streubel, G. von Frantzius, W. Marten, *J. Chem. Phys.*, **2003**, *119*, 165–169.

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